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DEVELOPMENT OF RUSSIAN ROCKET ENGINE TECHNOLOGY

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FROM THE AUTHOR

The achievements in the mastery of space have attracted the /3* attention of mankind to various problems of astronautics, including problems of the history of its development. In the USSR in recent years we have seen increasing interest in the study and analysis of the documents from the archives describing the development of domestic rocket technology. It is gratifying to note that the teams of scientific workers in this area are growing -- the history of astronautics is now being studied not only be veterans of rocket technology, but also by young specialists as well.

Various periods are studied -- before the October Revolution, before the beginning of the Great Patriotic War, before the launch of the world's first artificial satellite (4 October 1957), before and after the first flight of man in space (12 April 1961). Additional periods have been determined by new achievements in the mastery and study of space -- by successful flights to Venus and Mars, soft landings on the moon and Venus, launching of automatic interplanetary stations, unique experiments with manned spacecraft, etc. Widely varied aspects of the history of astronautics are being studied deeply: the development of the design of rockets and engines of various types, the work of experimental-design, scientific research, administrative, party and social organizations, the activity of individual persons. Therefore, it is impossible at present to speak of the history of rocket and space technology as a single theme, to attempt to write an all-encompassing book on the development of astronautics, or to pretend completeness of presentation.

This book is dedicated to the history of the creation and development of Soviet liquid-fueled rocket engines [LRE] (as we know, LRE are the most important engines in modern astronautics).

The author has attempted to describe the contribution made /4 by our countrymen K. E. Tsiolkovskiy, Yu. V. Kondratyuk, F. A. Tsander, V. P. Glushko, S. P. Korolev, M. K. Tikhonravov and others to the science of rockets and rocket engines burning liquid fuels, as well as the successes achieved during the Great Patriotic War in the preparation of the fundamental basis for the further development of rocket engine construction, and most importantly to show the basic role of the gas dynamic laboratory

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*Numbers in the margin indicate pagination in the foreign text.

(GDL), Group for the Study of Reaction Engines (GIRD) and the world's first Reaction Scientific Research Institute (RNII).

The author found it impossible to analyze all of the engines designed and produced in the USSR. However, in order that the reader might gain a more complete concept of the interrelationship of the widely varied and highly complex problems solved in the creation of engines, some LRE designs are described rather completely.

The book was written utilizing materials from the archives of the Academy of Sciences USSR, the GDL Experimental and Design Bureau and many other organizations. Many comrades kindly provided the results of their own historical studies and made useful recommendations during the preparation of the manuscript. The author is truly grateful to all those comrades who took part in the creation of this book, and particularly to N. V. Ivanov, V. M. Komarov and D. A. Shushko.

First must come thought, imagination and dreams. They are followed by scientific calculation. Then, finally, the thought is brought to life.

K. E. Tsiolkovskiy

Chapter 1. The Period of Theoretical Foundation of the Capabilities and Areas of Application of LRE /5

1.1. At the Wellsprings of Soviet Rocket Design

The development of rocket technology before the 17th century has been very little studied. The first reliable information on the use of rockets in Russia relates to the last half of the 17th century. In 1680, an "institution" was created in Moscow, where firework rockets were manufactured. The production of powder rockets in Russia expanded continually after that time, but these rockets were quite primitive, even during the latter half of the 18th century.

After the use of military rockets by the English army in the seige of Bulon and Copenhagen in 1805-1807, a military scientific committee began to study military rockets in Russia. After a number of unsuccessful experiments, a member of the military scientific committee named Kartmazov made two types of military rockets in 1814 -- incendiary and explosive. In 1815, the famous artillery scientist A. D. Zasyadko (1779-1837) began to perform experiments with military rockets. In 1832, all the "rocket institutions" in Russia were combined into the Peterburg Rocket Institution, which served as a center for the creation and manufacture of domestic military rockets. Until the mid-1840's, rocket building in Russia developed slowly, producing low quality rockets due to the primitive state of the technology of their production. Then, due to the wide use of rockets during military actions in the Caucasus, the attitude toward problems of improvement and production of rockets in Russia /6
changed sharply. At this time, the greatest Russian artillery scientist, Konstantin Ivanovich Konstantinov (1818-1871) began to work on the development of rockets. By 1845, 1000 two-inch military rockets were delivered to the Caucasus. The quality of the military rockets produced by the Peterburg Rocket Institution was significantly improved. By the mid-1850's, military rockets were widely used and proved their utility. As a result of this, military rockets were made a part of the armament of the Russian army and navy.

In the 1850's and 60's, K. I. Konstantinov published several works on problems of the production and use of rockets. K. I. Konstantinov first noted that the eccentricity of the reaction force was one of the main reasons for scattering of rocket impacts. Discussing the principle of motion of rockets, he noted that as the powder burned, the impulse imparted to the rocket was equal to the impulse of the exhaust gasses. Thus, K. I. Konstantinov first formulated the basic law of motion of rockets, although the mathematical interpretation and production of a formula for determination of the flight velocity of rockets were not developed in the works of K. I. Konstantinov.

The possibility of the application of rocket motors for human flight attracted the attention of many of our engineers, inventors, designers and scientists. For example, in 1849 I. I. Tretesskiy (1821-1895) developed plans for rocket powered flight vehicles, to be powered by steam. In 1866, N. M. Sokovnin (1811-1894), in his work Vozdushnyy Korabl' [The Airship], described an aerostat design to be driven by reaction force. In 1867, N. A. Teleshev was awarded a patent for a jet airplane. In 1880, the talented scientist and inventor S. S. Nezhdanovskiy, based on theoretical studies, calculations and computations, concluded the possibility of construction of a reactively powered flight vehicle. Between 1882 and 1884, he studied the problems of the energetics of reaction motors, analyzing the possibility of using liquid two-component fuels for rockets[1]. In 1887, F. R. Geshvend in his brochure "General Basis of the Design of a Steamship for Air Travel," suggested a plan for a vehicle with a steam reaction engine. In 1896, A. P. Fedorov in his brochure "A New Principle of Air Flight" abandoned the atmosphere as a supporting medium and presented a description of a reaction motor in which gas was to flow from a central tube (cylinder). /7

This hardly exhausts the list of Russian researchers and inventions dedicated to problems of reaction flight. Among these efforts we should particularly note the work of N. I. Kibal'chich (1853-1881).

Nikolay Ivanovich Kibal'chich, the author of the world's first plan for a rocket flight vehicle[2], was born 19 October 1853[3] in the city of Korop. In his sixth year in school, he

[1]The works of S. S. Nezhdanovskiy were published only in 1964. The notebooks and drawings of S. S. Nezhdanovskiy are stored in the N. Ye. Zhukovskiy Museum of Scientific Memorabilia in Moscow.

[2]Kibal'chich, N. I., A Plan for an Aircraft, Byloye, 1918, No. 10-11.

[3]Here and throughout the book, all dates from the prerevolutionary period are given in the old style.

participated actively in the creation of secret libraries containing illegal publications of D. I. Pisarev, N. G. Chernyshevskiy, A. I. Gertsen, N. P. Ogarev, and edited the school manuscript journal, writing for it articles on Stepan Razin, Yemel'yan Pugachev and the French revolution. In 1871, N. I. Kibal'chich entered the Peterburg Transportation Institute, and in 1873 -- the Medical-Surgical Academy.

In 1878, N. I. Kibal'chich went over to an illegal position and began leading an underground explosives laboratory, set up by the Executive Committee for the People's Will; at the same time, he studied the possibilities of the use of powder for flight vehicles and criticized scientists attempting to solve the problem of human slight by copying the flight of birds. /8

Nikolay Ivanovich Kibal'chich

N. I. Kibal'chich was arrested in connection with the murder of Tsar Alexander II on 17 March 1881. On 23 March 1881, just before entering prison, he published his plan for a flight vehicle based on the principle of reaction motion.

At the beginning of his plan, the author gave his reason for selecting his working fluid and source of energy. He wrote that no other substances could liberate energy in such large quantities in such short periods of time as explosives. For the first time, he stated the ideal of the possibility of using blastic powder and the need to assure a programmed mode of burning of the powder. The plan studied fuel-feeding and regulating devices, as well as problems of ignition. He suggested that powder charges be fed to the combustion chamber by automatic clockwork mechanisms. N. I. Kibal'chich also studied the problem of the stability of flight and noted that flight could be stabilized both by proper arrangement of mass and by means of stabilizing wings. The plan also discussed the problem of slowing the vehicle up on descent. At the end of his explanatory note, the author set forth the opinion that success in solution of the problem depends on the selection of the relationship between the payload mass, dimensions of powder charges and geometry of the combustion chamber -- the main portion of the apparatus.

The plan of N. I. Kibal'chich is a very brave attempt to solve the problem of creation of a flight vehicle. Unable

to perform experiments, the author developed his idea on the basis of guesses and scientific calculations.

We have presented a brief biography of N. I. Kibal'chich, since the life of this remarkable son of the Ukrainian nation has been described repeatedly in the popular and special literature. However, even now certain facts remain unclear. Some historians, for example, consider the question of Kibal' chich's place of residence during the last days of his life still unanswered.

On 20 January 1960, a memorial museum was opened in the home where Mikola (Nikolay) Kibal'chich spent his childhood.

The name of Kibal'chich has been given to a crater on the far side of the moon.

1.2. The Works of N. Ye. Zhukovskiy and I. V. Meshcherskiy /9

During the second half of the last century, 1830-1890, the first works of two outstanding Russian scientists appeared -- Nikolay Yegorovich Zhukovskiy and Ivan Vsevolodovich Meshcherskiy. These studies were dedicated to problems of reaction-powered motion.

The founder of modern aeromechanics and hydromechanics, Nikolay Yegorovich Zhukovskiy, was born on 5 January 1847. His childhood was spent in the village of Orekhovo, in the Vladimirskaya region. N. Ye. Zhukovskiy received his secondary education at the Fourth Moscow Gymnasium. After completion of the gymnasium, he entered Moscow University, where he participated from his very first year in the work of the club which later became the Moscow Mathematical Society. Graduating from the University in 1868, N. Ye. Zhukovskiy, who always dreamed of becoming an engineer, entered the Peterburg Institute of Railroads[1].

Beginning in 1870, N. Ye. Zhukovskiy was an instructor of physics at the Second Moscow Women's Gymnasium, until in 1872 he transferred to the Imperial Moscow Technical School (now the Moscow Higher Technical School imeni Bauman). At first, N. Ye. Zhukovskiy taught mathematics, then for 47 years -- mechanics. It was at this school that Nikolay Yegorovich began to study one of the most complex and interesting sections of theoretical physics -- hydromechanics. The results of his first studies were published by N. Ye. Zhukovskiy in his dissertation "The

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[1]"Astronautics," Moscow, Sovetskaya Entsiklopediya [Soviet Encyclopedia], 1970.

Kinematics of a Liquid Body." After an outstanding defense in 1877, Nikolay Yegorovich was awarded the degree of Master of Science. In 1879, N. Ye. Zhukovskiy was selected as a supernumerary professor of analytic mechanics by Moscow University. In 1882, he published his original work "On the Reaction of Inflowing and Outflowing Fluids," in which he first produced the formulas for determination of the reaction force of a stream of fluid flowing from a moving vessel. His monograph "The Strength of Motion," written in 1887, won N. Ye. Zhukovskiy the degree of Doctor of Applied Mechanics.

Ne. Ye. Zhukovskiy was given great latitude for comprehensive scientific activity, both in the technical school and in the university where later, in 1891, N. Ye. Zhukovskiy was made an ordinary professor.

By the end of his life, N. Ye. Zhukovskiy had become the organized leader of the domestic school of hydroaeromechanics. Constantly developing the theoretical principles of the mechanics of an incompressible fluid, N. Ye. Zhukovskiy published works between 1890 and 1907 which laid the foundation for a new science -- the dynamics of the flight of aircraft. In 1902, under the leadership of N. Ye. Zhukovskiy, one of the world's first wind tunnels was created, in 1904 -- the first aerodynamics institute in Europe, and in 1910 -- the aerodynamics laboratory of IMTU. In 1908, Zhukovskiy published his work "On the Theory of Vessels Powered by the Reaction Force of a Stream of Water."

The Great October Socialist Revolution opened a new stage in the development of domestic aviation science and technology.

In 1918, the Central Aerohydrodynamic Scientific Research Institute (TsAGI) was organized, headed by N. Ye. Zhukovskiy. The theoretical courses of MVTU served as a basis for the creation of the Aviation Technical School, converted in 1921 to the Institute of the Red Airforce [IKVF]. In 1922, based on this institute, the Military Air Academy imeni N. Ye. Zhukovskiy, now the Military Air Engineering Academy imeni N. Ye. Zhukovskiy, was created. /10

V. I. Lenin, beginning in the very first days of Soviet power, constantly followed the work of N. Ye. Zhukovskiy and his scientists and gave them comprehensive aid. N. Ye. Zhukovskiy was called by Vladimir Il'ich Lenin the "father of Russian Aviation."

The works of Nikolay Yegorovich in the area of aerodynamics and flight served as the theoretical basis of modern aviation science.

Nikolay Yegorovich Zhukovskiy

N. Ye. Zhukovskiy spoke out publicly on the problem of reaction motion for aircraft for the first time on 1 November 1881 at a meeting of the Polytechnical Society of the Moscow Higher Technical School [MVTU] in connection with the publication of the brochure "On Aerostats" by V. Merchinskiy. N. Ye. Zhukovskiy showed the inconsistency of the device described in this brochure, based on the use of the reaction of a stream of mercury flowing from a tube to control the vertical motion of an aerostat.

In November of 1881, at a meeting of the Physical Sciences Section of the Society for Natural Sciences Enthusiasts in Moscow, N. Ye. Zhukovskiy read a report "On the Reaction of Inflowing and Outflowing Fluids." His work represented a significant contribution to the theory of reaction motion[1]. In it, N. Ye. Zhukovskiy reported the results of his own studies on the determination of the reaction force acting on a vessel submerged in a fluid caused by forcing out or sucking in a fluid through a side tube. He showed that the reverse reaction (reaction upon sucking in of a fluid) is very slight in comparison to the direct reaction caused by expulsion of a fluid. /11

Thus, N. Ye. Zhukovskiy showed that by successively sucking in and expelling water, a vessel can be made to move in the direction opposite to the expulsion of the water. The report was confirmed by the results of experiments, which were demonstrated to those present. On 17 December 1885 at a meeting of the Mathematical Society, N. Ye. Zhukovskiy once more returned to this theme in his report "The Reaction of Inflowing and Outflowing Fluids," published in 1886[2]. In this report, N. Ye. Zhukovskiy noted that the reaction of the inflowing fluid is negligible, no matter how it is drawn into the vessel. He explained the significant force of the direct reaction from the physical standpoint by the fact that the external liquid mass flows into the vessel from all directions at continually varying speeds, whereas upon expulsion a directed stream is formed with a speed which is multiplied by the flow rate per second to give the reactionforce produced.

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[1] Zhurnal Russk. Fiz Khim. Ob-va, No. 4, Nov. 1882, pp. 470-475.

[2] Matem. Sborn. 1885, Vol. XII, No. 4, pp. 787-796.

In his work, N. Ye. Zhukovskiy theoretically predicted a number of possible flight trajectories of an aircraft, in particular the "dead loop." In 1904, he discovered the law determining the lift of an aircraft wing and published the results of his investigations on this problem in 1906.

His final work on the theory of reaction engines was the article "The Theory of Vessels Driven by the Reaction Force of a Stream of Water," printed in 1908. It presents an objective analysis of the problem of the reaction force for vessels of any shape, submerged in a fluid and moving at arbitrary speed, with fluid flowing in and out of the vessel. In this report, N. Ye. Zhukovskiy avoided the error of certain scientists: he noted that the phenomenon of reaction must be studied together with /12
the factors influencing the resistance to the motion of the vessel, and analyzed the change of this resistance as a function of the point where the liquid was drawn into the vessel.

Ivan Vsevolodovich Meshcherskiy made a significant contribution to the theory of reaction motion.

Ivan Vsevolodovich Meshcherskiy was born on 29 July 1959 in the city of Arkhangel'sk. After secondary school, he entered the University of Peterburg in the Physics and Mathematics Department in 1878. Here Ivan Vsevolodovich showed great interest in scientific research work and, after his graduation in 1882, he remained at the University. In 1890, he began his teaching activity as a teaching assistant at Peterburg University. In 1891, I. V. Meshcherskiy was selected as the Head of the Department of Mechanics of the Peterburg Higher Courses for Women, and in 1902 he headed the Department of Theoretical Mechanics of Peterburg Polytechnical Institute, where he worked through the rest of his life.

The name of Meshcherskiy has been given to one of the craters on the far side of the moon.

The most important works of I. V. Meshcherskiy were dedicated to a new section of theoretical mechanics -- the mechanics of bodies of variable mass, the basis of rocket dynamics. The significance of this science results from the fact that it allows precise calculation of the motion of a rocket and determination of conditions under which rockets will reach given orbits or trajectories with the minimum expenditure of energy, /13
and allows many problems related to the creation of rocket engines to be solved, leading directly to success in the penetration of space.

Ivan Vsevolodovich Meshcherskiy

The first studies of I. V. Meshcherskiy on the theory of the motion of bodies of variable mass became known in 1893 when he read a report to the Mathematical Society of Peterburg on the theme: "One Particular Case of the Theorem of Gulden." The principles of this theory were set forth in his master's dissertaion "The Dynamics of a Point of Variable Mass," which he defended in 1897. In this work for the first time an equation was produced for the motion of a point of variable mass for the case of separation or attachment of particles, in particular the vertical motion of a rocket. In 1904, I. V. Meshcherskiy completed his work "The Equationsof Motion of a Point of Variable Mass in the General Case," presenting a general theory of motion for the case of attachment and separation of particles. It was shown in these works that when particles with zero relative velocity are attached or separated, the reactive force is equal to zero. However, if the relative speed of the particles is not equal to zero, supplementary forces will act on the body: a reactive force in the case of separation of particles and a resistance force in the case of attachment. The final work in this direction was an article by I. V. Meshcherskiy entitled "A Problem from the Dynamics of Variable Masses" (1918), in which he studied the motion of a system of points with variable masses.

I. V. Meshcherskiy was not only a remarkable scientist, but also an outstanding teacher. He fundamentally changed the teaching of the course on theoretical mechanics, bringing it closer to the needs of practice. He trained engineers, many of whom later became great scientists, including specialists in the area of rocket and space technology.

1.3. K. E. Tsiolkovskiy, the Founder of Astronautics

The idea of flight with rockets, i.e., flight vehicles moved by the effect of the reaction force, arising when a portion of the mass of the vehicle is expelled, was given a deep scientific basis in the works of the outstanding Russian scientist, Konstantin Eduardovich Tsiolkovskiy (1857-1935). K. E. Tsiolkovskiy suggested a rocket with a liquid fueled motor, theoretically studied some of the specifics of the operation of individual units and of the engine as a whole during /14

flight in space, created the principles of the theory and design of LRE. One of the fundamental problems developed and studied by K. E. Tsiolkovskiy was the movement of rockets as bodies of variable mass; these studied laid the foundation for the theory of rocket flight. The scientific activity of K. E. Tsiolkovskiy was multifaceted and unique. To his pen belong original works on aerodynamics, the theory of interplanetary voyages, work on the problem of life on artificial islands in space, on biology, geophysics and philosophy.

Konstantin Eduardovich Tsiolkovskiy (1899 photo)

Konstantin Eduardovich Tsiolkovskiy was born on 17 September 1857 in the village of Izhevskiy, Spassky district, Ryazanskiy region in the family of a forester. His childhood years were marred by serious illness; at the age of 9, he almost lost his hearing. This made it impossible for Tsiolkovskiy to enter school. The mother of Konstantin Eduardovich -- Mariya Ivanovno Tsiolkovskaya-Yumasheva (1830-1870) -- taught her son herself, teaching him to love work. At age 14, Konstantin Eduardovich began to study independently, using the books of his father Eduard Igant'yevich Tsiolkovskiy (1820-1880), who noticed the capability of his son and his love for scientific experiments. His father helped him to make balloons, to construct models of various machines, inspiring young Tsiolkovskiy with a love for technology, nature and experiments, teaching him to analyze the results even of the simplest experiments.

Tsiolkovskiy was 16 years old when his father sent him to Moscow. During these years, Konstantin Eduardovich developed an interest in space flight. /15

In 1879, Tsiolkovskiy passed the examination and was named a Teacher of the People's School and in 1880, he began teaching arithmetic and geometry at the Borovskiy School in Kaluga region. Here Konstantin Eduardovich Tsiolkovskiy performed his first studies on the subject of interplanetary voyages.

The dream of traveling in space did not leave the scientist throughout his life. His studies on the theory of reaction motion are broad in scope and show a surprising combination of strict mathematical analysis with brave flights of fantasy. K. E. Tsiolkovskiy believed in the immortality of developing

mankind, and all his creative activity, in the final analysis, was dedicated to seeking out means for the improvement of the living conditions of future generations.

In order to solve the primary problem -- the overcoming of the Earth's gravity -- the scientist had to solve many problems, widely varied in content and complexity.

In 1881, K. E. Tsiolkovskiy worked on problems of the kinetic theory of gasses. For his work entitled "The Mechanics of the Animal Organism," he was selected as a member of the Physical-Chemical Society.

Beginning in 1883, Konstantin Eduardovich dedicated his time primarily to problems of flight in the air and in space. On 20 February of that year, Konstantin Eduardovich completed the manuscript to "Free Space," in which he described the properties of the medium and the conditions of movement in space. Here he analyzed the design of a "shell for voyages in free space."

His works on the design of an all-metal controlled dirigible became widely known. He set himself the task of creating a metal controlled aerostat, turning his attention to the essential shortcoming of dirigibles with balloons made of rubberized materials: these envelopes wore rapidly, represented a danger of fire, were low in strength, and the gas which filled them diffused through the fabric and was rapidly lost.

The progressive, for its time, dirigible plan was not supported; the author was not even given a subsidy to construct a small model. In order to test a number of his own calculated data and prove the possibility of constructing his dirigible, K. E. Tsiolkovskiy made a model at his own expense. /16

In 1897, K. E. Tsiolkovskiy constructed the first wind tunnel in Russia, developed his model testing methodology and achived interesting results. In 1900, K. E. Tsiolkovskiy tested several models which he had made in the wind tunnel and determined the drag factors of bodies of various shapes.

In 1895, his science fiction story "On the Moon" and the work "Dreams of the Earth and the Sky" were published. The first work, in particular, describes how people who found themselves on the moon would feel, while the second work, in addition to presenting many original thoughts, sets forth the idea of the creation of a "falling laboratory" and describes various phenomena occurring in weightlessness.

This idea of reproduction of the conditions of weightlessness is based on the fact that if a man is placed in a flight vehicle which moves toward the Earth at an acceleration equal to the acceleration of the force of gravity, the force of the interaction of the man with his support (the wall of the cabin of the flight vehicle) will be zero, i.e., the acceleration will be equal to zero, and the man will be under conditions of weightlessness. A state near weightlessness is experienced by a pilot at the peak of a climb. "Falling laboratories" are presently used for training of astronauts and to study phenomena occurring under conditions of weightlessness.

The style of the work of K. E. Tsiolkovskiy is distinctive and unique. His persistence in seeking out the most convincing and simplest (and consequently most possible) solution, his tendency to produce a clear picture both from the physical and mathematical standpoints -- these are the characteristic features of the style of K. E. Tsiolkovskiy which have made his works understandable, readable and convincing.

Konstantin Eduardovich wrote, "I have been studying reaction devices since 1895. Only now, after 34 years of work, have I come to a very simple conclusion concerning the proper system."[1] And further, "In 1896, I purchased a book by A. P. Fedorov entitled 'A New Principle for Air Travel' (Peterburg, 1896). This book seemed to me to be unclear (since no calculations were made). In such cases, I perform my calculations independently, from the very beginning. This was the beginning of my theoretical studies on the possibility of using reaction devices for space voyages."[2]

In 1892, Konstantin Eduardovich moved to Kaluga. Years /17
filled with productive, creative labor passed in this city. K. E. Tsiolkovskiy produced his formulas for rocket travel, allowing him to solve the problem of the most realistic method of mastery (study) of space in the theoretical plane.

Konstantin Eduardovich Tsiolkovskiy lived 29 years in the house on the corner of what is now K. E. Tsiolkovskiy Street and Sovkhoznoy Street. Konstantin Eduardovich bought this one-story house in 1904. In 1908, the house was expanded, adding a second story -- a sun room and veranda. In the fall of 1933, the family of the scientist moved to a large, well-built home given to K. E. Tsiolkovskiy by the Kaluga City Council of Worker's Deputies.

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 296.

[2] Ibid., p. 179.

The Home of K. E. Tsiolkovskiy in Kaluga

On 19 September 1936, a memorial museum was opened in the old home. Most visitors to the museum begin on the second floor. There, in a small entrance hall, is a portrait of the scientist at age 75. A small showcase contains personal belongings, photographs of the family, portraits of scientists who were friends of K. E. Tsiolkovskiy. Here also is the bicycle which Tsiolkovskiy used far into his old age. The sun room was his office and bedroom. By his desk are two comfortable chairs. A wire is strung across the room, and from it hangs a kerosene lantern. On the veranda is a homemade lathe and small workbench. Here also is a bending machine with wooden rolls and specimens of corrugated sheet metal for a dirigible.

On the first floor, in what was a storage room, the works of the scientist on dirigible building and aerodynamics are displayed. The display stands show models of the all-metal dirigible, equipment for manufacturing its shell. One small /18
room on the first floor contains the model wind tunnel made by K. E. Tsiolkovskiy.

A larger room contains the published works of K. E. Tsiolkovskiy, models of his rockets, drawings, plans and literature on his works. In the garden outside the museum house is a bust of K. E. Tsiolkovskiy.

Considering the great interest in problems of rocket technology in Kaluga, construction was undertaken of a new building for the museum, which was dedicated on 13 June 1961. Today, the K. E. Tsiolkovskiy State Museum of the History of Astronautics stands on Academician Korolev Street in the shade of the trees of an old park. The Museum stands on the banks of the Oka and Yachenka Rivers, with a view to the horizon. The limitless spaces of Russia merge here with the infinity of space, to the glory of man and his inexhaustible imagination. The Museum of the History of Astronautics -- "the Space Palace" -- tells the story of the life and activity of Konstantin Eduardovich, the development and practical application of his remarkable

ideas. The cases and displays help the visitor to familiarize himself with the works of the scientist.

The K. E. Tsiolkovskiy State Museum of the History of Astronautics in Kaluga

In 1903, in his work "Investigation of Space Using Reaction Devices,"[1] and in many other works published in 1911-1912, 1914 and 1926, as well as "Space Rocket Voyages," published in 1929, K. E. Tsiolkovskiy clearly and accurately laid the foundation of the theory of rocket travel, described the principles of the design of rockets and rocket engines burning liquid fuel. He studied and recommended various fuels for rocket engines. K. E. Tsiolkovskiy did not exclude the possibility of using atomic energy in rocket technology. /19

The works of Tsiolkovskiy also studied problems related to the mastery of interplanetary space. He proved that from interplanetary stations to flights to the planets, the trail could be blazed to grandiose settlements in space, to the use of the riches of space for the needs of mankind.

K. E. Tsiolkovskiy suggested that the construction material to be used for "settlements" should be the asteroids, also called the "small planets," moving around the sun in elliptical orbits, mostly located between the orbits of Mars and Jupiter.

The total mass of the asteroids amounts to about 1000th of the mass of the Earth. The largest asteroids are a few hundreds of kilometers in diameter. Some of the small planets, during the process of their movement, come rather close to the Earth. The small planet Icarius, for example, came within 6.5 million kilometers of the Earth in 1968, while Hermes passed the Earth at a distance of about 380,000 km in 1937 (the distance from the Earth to the moon is 384,400 km).

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[1] First printed in the journal Nauchnoye Obozreniye, No. 5, 1903.

Before the Great October Socialist Revolution, K. E. Tsiolkovskiy and his works were not properly acknowledged. Only in the Soviet state was he given the proper concern and attention. "Under the Soviet government," Konstantin Eduardovich wrote, "I could give myself freely to my work, and, although almost unnoticed before, my works now attracted attention." In 1919, he was confirmed as a member of the Socialist, later Communist Academy. Since in 1920, K. E. Tsiolkovskiy retired from teaching in the secondary school due to his age of 63 years and poor health, he was awarded a personal pension by a state decree. Public organizations helped K. E. Tsiolkovskiy constantly.

The thoughts of K. E. Tsiolkovskiy, set forth in his books, still show his great boldness, his mathematical strictness and the accuracy of his vision.

Between 1917 and 1935, four times more of his articles, brochures and books were published than during the entire pre-revolutionary period. In the ten years from 1925 to 1935 alone, about 60 works by K. E. Tsiolkovskiy were published on physics, astronautics, astronomy, mechanics and philosophy.

Konstantin Eduardovich Tsiolkovskiy

In 1932, the entire country celebrated his 70th birthday and his 50th year of creative scientific activity. The USSR Academy of Sciences held a solemn meeting in celebration in Moscow, and Tsiolkovskiy attended. /20

Soon he visited the capital once more, when M. I. Kalinin awarded him the Red Banner Labor Award for his creative service to his country. Accepting the award, K. E. Tsiolkovskiy stated, "I can thank the government for this high award only by further work."

During the last years of the life of K. E. Tsiolkovskiy, he worked toward the popularization of his ideas, frequently lecturing, appearing in discussions and reading reports before soldiers, workers, scientists and farmers.

The works of K. E. Tsiolkovskiy have been described by such scientists as V. P. Glushko, N. A. Rynin, Ya. I. Perel'man, V. V. Ryumin and other successors and popularizers of the ideas of Konstantin Eduardovich -- S. P. Korolev, M. K. Tikhonravov,

A. A. Kosmodem'yanskiy. Their books, brochures and articles have carried the ideas of the scientist to the masses, stimulating interest in problems of the study of space and multiplying the ranks of rocket technology enthusiasts.

Beginning with the first weeks of existence of the Reaction Scientific Research Institute [RNII], which was created in Moscow in September of 1933, scientific contact and fruitful correspondence were held between K. E. Tsiolkovskiy and the Institute. For example, in February of 1934 he composed a "Program for the Work of the RNII," and in March of that same year he wrote his article "The Energy of Chemical Compounds and the Selection of Component Parts for an Explosion," etc.

In August of 1935, K. E. Tsiolkovskiy's health began to deteriorate. On 13 September 1935, the scientist sent a letter to the Central Committee of the Party. "All my life I have dreamed that my works might move mankind forward, at least a little. Before the revolution, my dream was impossible. Only October brought recognition to my works... I have felt a love for the people, which has given me strength to continue my work, even in my illness. However, my health will not allow me to finish the work I have begun. All my labors on aviation, rocket flight and interplanetary voyages I bequeath to the Bolshevik party and the Soviet government -- the true leaders of the progress of human culture. I am sure that they will successfully complete my labors."[1] /21

Exceptionally valuable and progressive works of K. E. Tsiolkovskiy are his works on reaction motion, which preceded the development of science in this area by many decades. K. E. Tsiolkovskiy first developed the laws of motion of a rocket as a body of variable mass, indicating efficient paths for the development of astronautics and rocket building. He found a number of important engineering solutions to problems of rocket design, he analyzed and recommended fuels for use for rocket engines. K. E. Tsiolkovskiy laid the foundations of the theory of LRE.

A number of the technical ideas of K. E. Tsiolkovskiy were applied in the creation of modern rocket engines, rockets and spacecraft.

Since 1966, on 17 September each year in Kaluga readings are held dedicated to the development of the scientific heritage of K. E. Tsiolkovskiy.

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[1]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 20.

The readings are conducted by the State Museum of the History of Astronautics, the Commission for the Development of the Scientific Heritage of K. E. Tsiolkovskiy of the Academy of Sciences USSR, the Astronautics Committee of DOSAAF USSR, the Institute of the History of Science and Technology, Academy of Sciences USSR and the Institute for Medical and Biological Problems of the USSR Public Health Ministry. Soviet scientists discuss the most pressing problems of missile and space technology and rocket engine construction at these readings.

The Works of K. E. Tsiolkovskiy on the Creation of the Theory of Reaction Engines

One of the achievements of K. E. Tsiolkovskiy is the determination of the expediency of the use of LRE as spacecraft engines. He suggested a plan for a rocket equipped with an LRE, determined the areas of application of such engines, selected and evaluated various types of rocket fuels, i.e., /22
substances or combinations of substances to serve as the source of energy and working fluid for a rocket engine, studied some of the design peculiarities of individual units and of the engine and its operating conditions, and noted the main paths to be followed in the creation of powerful liquid-fueled rocket engines.

The power of a rocket engine is equal to the kinetic energy of the mass of gases in the reaction stream flowing from the reaction engine per second, or half the product of the thrust times the effective exhaust velocity. The power of the engines of modern booster rockets reaches tens of millions of kilowatts.

K. E. Tsiolkovskiy pointed out many scientific and technical problems which had to be solved during the course of further development and improvement of rockets and their engines.

The selection of a plan for a rocket engine is a difficult task. In order to properly select a plan, one must consider the values of the fixed parameters of the engine, the purpose of the rocket, its range of flight, the level of technology in the country and available experience. If the problem is to be solved today, one plan will be suggested; for rockets of the future -- another. K. E. Tsiolkovskiy suggested a plan for a rocket and a rocket engine for the future, considering the possible progress of science and technology. He believed that the time had come to begin such development. Later events have confirmed the correctness of his views. Modern engines and rockets do not differ in principle from those he suggested: a two-component liquid fuel, pumped fuel feed, acceleration of the gas jet in a nozzle, etc.

In his work "Investigation of Space with Reaction Devices" (1903), K. E. Tsiolkovskiy described the plan and operating principle of an LRE using liquified gasses as components in the following words. "The chamber[1] contains a great reserve of substances which, when mixed, immediately form an explosive mass. These substances, fully and evenly exploding in the area set aside for this purpose, then flow as hot gases through tubes which expand at the end like a horn or other musical instrument."[2]

The combustion chamber of a rocket engine is the most important part of the rocket engine, which creates the reaction force due to the flow of the working fluid. A modern rocket engine consists of a combustion chamber and nozzle. The nozzle /23
is that portion of the rocket engine in which the thermal energy of the compressed working fluid -- the combustion products -- is transformed to kinetic energy, i.e., the gas jet is accelerated to the exhaust velocity.

Further, K. E. Tsiolkovskiy wrote, "In one, narrow end of the tube, the explosive substances are mixed: thence, flaming gases are produced here. In the other, expanding end, these gases, greatly rarefied and cooled, burst outward through the aperture with tremendous velocity.. The two fluid gases are separated by a barrier."[3]

In 1922, K. E. Tsiolkovskiy wrote an article entitled "Star Flight" for the magazine "Znaniye-Sila," in which he described a rocket with an LRE designed to be used as a jet aircraft. For this purpose, the rocket was equipped with wings.

In 1927 in Kaluga, K. E. Tsiolkovskiy published his work Kosmicheskaya Raketa. Opytnaya Podgotovka [Space Rocket. Experimental Preparation]. This work presents a still more detailed description of an LRE; it is pointed out that the fuel components must be fed to the combustion chamber by "...two pumps, driven by a single engine. The first pumps the oxygen compounds to the combustion chamber, the other pumps the hydrogen compounds."[4] Here also we find the idea of maintaining a certain ratio of fuel components during the operation of the LRE: "regulation is important: if there is more oxygen than needed, the combustion

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[1]Having in mind the interior of the rocket.

[2]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 73.

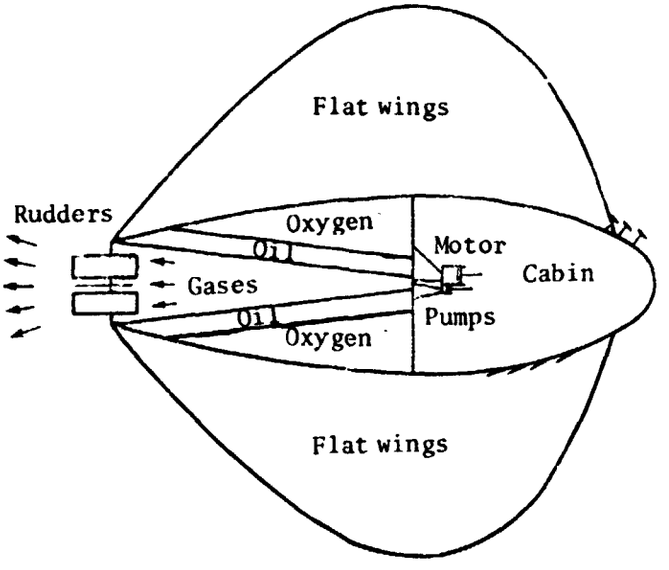
[3]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 261.

[4]Ibid., p. 75.

chamber itself might burn, if there is less -- the fuel will be expended uselessly."

In this same work, K. E. Tsiolkovskiy describes the operation of an LRE and studies the conditions needed to ensure safety. If a rocket were made according to these plans, published by Tsiolkovskiy early in the 20th century, the unused volume of the rocket would be very slight, since every free space, not occupied by structural elements, is filled with fuel; the LRE is submerged in the fuel components. This arrangement provides the minimum mass and size of rocket.

In his work "A Semireaction Stratoplane," first published in the magazine "Khochu Vse Znat'" in 1932, K. E. Tsiolkovskiy wrote, "In the lower layers of the atmosphere, an aircraft cannot reach a high velocity. ...my ideas and calculations have led me at present to the following, most possible type of high-altitude aircraft."[1] Further, K. E. Tsiolkovskiy presents a description of a jet engine[2] driving a propeller. /24



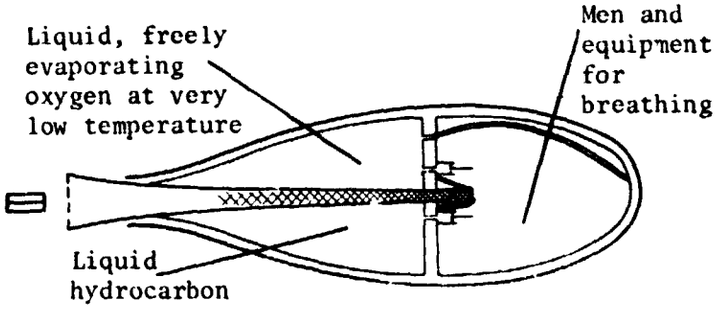
Plan from "Star Flight" by K. E. Tsiolkovskiy

/25

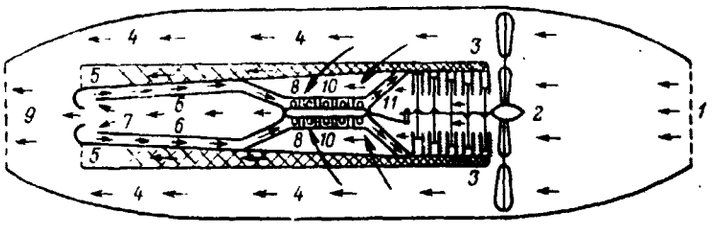
The design of the "semireaction stratoplane" developed by K. E. Tsiolkovskiy was as follows. As the device moves, air enters the internal portion of the body through adjustable inlet aperture 1. The gas stream is accelerated by propeller 2, driven by gasoline engine 3. The spent gases move through tubes 5 and flow out of their exhaust sections. The air and spent gases exhaust through adjustable nozzle 9. Air compressor 8 is

[1]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 389.

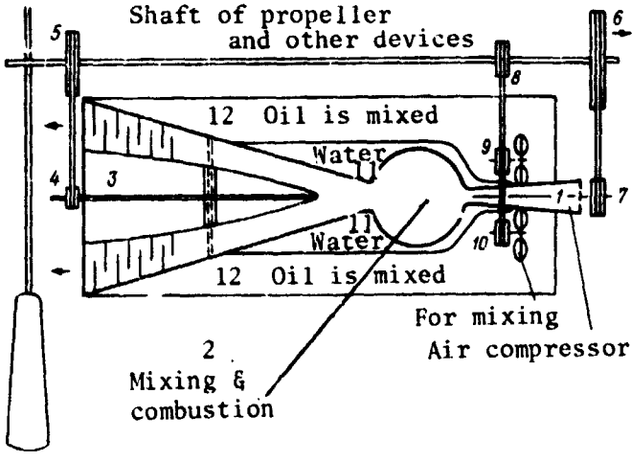
[2]A jet engine refers to a reaction engine which utilizes the air around the vehicle to burn the fuel.



Plan of Liquid-Fueled Space Rocket of K. E. Tsiolkovskiy



Plan of "Semireaction Stratoplane" of K. E. Tsiolkovskiy



Plan of the "Steam-Gas Turbine Engine for a Dirigible" of K. E. Tsiolkovskiy

mounted on a common shaft with engine 3. Air from cavity 4 partially enters cavity 10, then cavity 6 and, through annular space 7, it moves past tubes 5. Washing over these tubes, the air is cooled and enters the compressor. The compressed air flows through tubes 11 to the gasoline engine. /26

Finally, in his work "A Steam-Gas Turbine Engine," published in 1934, Konstantin Eduardovich suggested a unique turbocompressor engine, which he suggested be used for dirigibles. This engine is a prototype of one version of modern jet engines. In this engine, the incident air stream is sent by means of compressor 7 and diffusor 1 into generator 2 under pressure, where the oil fed into the generator by a pump (not shown on the drawing) is burned. The combustion products spin multiple-stage turbine 3. The rotation of the turbine is transmitted through system 4-5 to a propeller, which drives the dirigible. Furthermore, the rotation is transmitted by system 6-7 to the compressor, and by system 8-9-10 to agitators, which continually mix the oil in order to equalize its temperature in tank 12. The generator is cooled by the water filling space 11.

Thus, K. E. Tsiolkovskiy suggested a plan for a liquid-fueled rocket and plans for jet engines as well. All of the plans which he suggested were later utilized in principle in practice.

The Formula of K. E. Tsiolkovskiy

The creation of the most efficient engine design continues to be one of the most important problems of rocket engine construction. The rockets suggested by Konstantin Eduardovich, naturally, were not developed by him to the stage of a complete plan. They were more like reports of new ideas, inventions, discoveries, but reports based on scientific and technical calculation.

The development of the theory of rocket engines and rockets in the works of K. E. Tsiolkovskiy and in the works of other authors are based largely on the formula which is known by the name of its author -- K. E. Tsiolkovskiy.

This is the basic formula for the motion of a rocket, defining its maximum velocity V, equal to the product of the absolute value of exhaust velocity W_a of the combustion products from the reaction nozzle times the natural logarithm of the ratio of the initial launch mass of the rocket M_0 to its final mass M_k (considering payload), remaining after fuel mass M_t is expended in flight: /27

$$V = W_a \ln \frac{M_0}{M_k} = W_a \ln\left(1 + \frac{M_т}{M_к}\right).$$

In calculating the motion of a rocket equipped with a modern LRE, if the difference $p_a - p_H$ is other than 0, W_a in the Tsiolkovskiy formula must be replaced by the effective velocity, which is

$$W_{eff} = W_a + \frac{F_a}{G}(p_a - p_H),$$

where F_a is the area of the nozzle exit plane;

G is the mass flow rate of fuel per second, equal to the flow rate of the combustion product;

p_a is the gas pressure at the nozzle exit plane;

p_H is the pressure of the surrounding medium at the flight altitude H.

The ratio M_t/M_k is called the Tsiolkovskiy number and is represented by the letter Ts.

This formula is developed in the work "Investigation of Space with Reaction Devices" (1903). Using the Tsiolkovskiy formula (in his 1903 work, K. E. Tsiolkovskiy call this formula the "relationship of masses in the rock , we can calculate also the velocity increment of the in dual stages of multistage rockets.

Tsiolkovskiy's formula was refined by him to consider the influence of the resistance of the surrounding medium and the forces of gravity on the final flight velocity of a rocket. This formula was the first step made in the development of the requirements for LRE; during the initial period of development of rocket technology, it allowed scientists to determine the primary paths for improvement of the design of an engine. It is understandable that, when modern engines are produced, all of the accumulated experience of rocket construction and engine construction, the achievements in neighboring areas of science and technology are used, attempting to satisfy the continuously growing demands on the design of rocket engines.

It follows from the formula of Tsiolkovskiy that in order to increase the flight velocity of a rocket, one must increase the Tsiolkovskiy number Ts and the effective exhaust velocity of the gases W_{eff}.

The exhaust velocity of the gases from the nozzle /28

$$W_a = \varphi\sqrt{2Q\eta_t + W_{in}^2},$$

where Q is the quantity of heat liberated upon combustion of a unit of mass of fuel;

η_t is the thermal efficiency;

W_{in} is the velocity of entry of the fuel components into the combustion chamber;

ϕ is the proportionality factor.

The higher the heating capacity of the fuel, the more heat is liberated upon its combustion. However, the same fuel components, depending on conditions, liberate different quantities of heat which, in particular, depends on the ratio of the components

$$k_1 = \frac{G_o}{G_f},$$

where G_o is the mass flow rate of oxidizer per second;

G_f is the mass flow rate of fuel per second.

The optimal relationship, for which the exhaust velocity reaches its maximum, depends for a given pressure in the combustion chamber on the type of fuel, degree of expansion of gases in the nozzle and a number of other factors.

In order to increase the completeness of combustion in the smallest possible chamber volume, the quality of spraying and mixing of the components must be improved. "The problem is that the force of the explosion in a given tube[1] depends on the completeness of mixing of the combustion elements."[2]

The more heat which is liberated during the combustion of a unit mass of fuel, the higher the energy characteristics of the products of combustion -- heat conduct and the product of the gas constant of the products of combustion $R = 848/\mu$ times their temperature T_i.

With a given heat liberation, as the mean molecular mass of the combustion products μ decreases, the gas temperature decreases, simplifying the solution of one of the most complex problems of rocket engine construction -- the problem of effective cooling of combustion chamber walls.

The thermal efficiency /29

$$\eta_t = 1 - \left(\frac{p_a}{p_i}\right)^{\frac{k-1}{k}}$$

[1]Having in mind the combustion chamber of the rocket engine.

[2]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 201.

characterizes the conversion of heat to kinetic energy of the combustion products flowing from the nozzle.

In order to select the best value of gas pressure in the nozzle exit plane p_a, we use the thrust formula

$$P = GW_{eff}.$$

We recall that in this formula G represents the mass flow of fuel per second, equal in the stable mode to the mass flow of combustion products per second. Analysis shows that in order to produce the maximum thrust, pressure p_a should be equal to the pressure of the surrounding medium p_H. If the pressure of the surrounding medium changes during the flight of a rocket, the equation $p_a = p_H$ can be maintained by changing the parameters of the combustion chamber or the critical cross-sectional area, or the nozzle exit plane area.

However, adjustable nozzles have not yet been created for LRE, forcing us to utilize a certain mean value of p_a, selected during the process of ballistic planning of a rocket to provide the maximum flight velocity at the end of the powered stage of flight with a fixed payload mass and the selected value of Tsiolkovskiy number.

If an engine must operate at very high altitudes or in space, where the pressure of the surrounding medium is very low, in order to increase the thermal efficiency, the lowest possible pressure should be maintained at the nozzle exit plane. If this pressure is fixed, the thermal efficiency can be increased by increasing the pressure in the combustion chamber, which also helps to improve the combustion conditions, decrease the size and mass of the combustion chamber.

In analyzing the operation of a combustion chamber, K. E. Tsiolkovskiy based his calculations on pressure p_i = 100 atm. This pressure could not be achieved by the first LRE.[1] For example, in engine 10 of the GIRD-Kh rocket (1933), the pressure in the combustion chamber was only 8 to 10 atm, while the ORM-50 and ORM-52 engines (GDL, 1933) achieved 20-25 atm, the RD-107 engine (GDL-OKB, 1954-1957) produced 60 atm, the RD-119 engine,

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[1]Here and in the following, the units of measurement are presented as in the archive materials.

developed in 1953-1962 (GDL-OKB) produced 80 atm, and later engines have produced still higher pressures. Thus, the pressure intuitively assigned by K. E. Tsiolkovskiy for the chamber was approximately equal to the pressures achieved by modern engines. /30

Comprehensive improvement of engines has increased their economy.[1]

For example, in engine number 10, the specific impulse achieved in test stand operation (1933) was 162-175 s, in the ORM-52 engine (1933) -- 210 s, while the specific impulse of the combustion chamber of the RD-119 in a vacuum reaches 358 s (1958-1962).

In order to increase the Tsiolkovskiy number

$$Ts = \frac{M_t}{M_k}$$

one should use fuel of the highest possible density ρ_t. This maintains the requirement mentioned above for a high value of the quantity of heat Q liberated in the combustion chamber in each second of operation. In order to decrease M_k, the parts of the rocket should be made of structural materials for which the ratio of strength (or yield point) to density is as high as possible.

The Tsiolkovskiy number can be increased during planning of a rocket by successful selection of a plan of motor, rocket in general and individual rocket units and by assuring operation of the units as near as possible to their optimal operating modes. If a pressure-expulsion fuel-feed system is used, the fuel tanks must be made with thick walls, but if a pump-feed system is used, tanks are maintained at low pressure and their walls can be made thin. Therefore, the Tsiolkovskiy number for large rockets is higher with a pump-feed system than with a pressure-expulsion system.

As we have stated, in determining the Tsiolkovskiy number for a rocket, mass M_k refers to the mass of the structure of the rocket and its systems, including the engine, the residual

[1]The economy of a rocket engine is defined by the specific impulse, the ratio of the thrust of the engine to the fuel consumption per second.

liquids and gases at the end of the powered portion of flight and the payload mass M_p (nose portion with instruments or cabin plus astronauts, etc.). With a given value of Tsiolkovskiy number, as the payload is increased, the mass of all the other elements of the rocket must be decreased, which is achieved by comprehensive improvement and lightening of the design, or the launch mass of the rocket (or each stage) must be increased by increasing fuel mass M_t.

The Tsiolkovskiy formula allows us to judge the effectiveness of utilization of the fuel energy of a rocket. K. E. Tsiolkovskiy defined the work performed by a rocket /31

$$L_p = \frac{1}{2} M_k V^2;$$

the work of the exhausted gases

$$L_a = \frac{1}{2} M_t W_a^2,$$

and calculated the efficiency of a rocket as the ratio of L_p to the sum of $L_p + L_a$.

The power of engines and frequency of launches have become so great that, considering the prospects for the development of rocket and space technology, the determination of means for increasing the total efficiency and its current values, calculated for various moments of operation of an engine, have become a very pressing problem. The great consumption of fuel expected in the near future has placed the problem of the creation of rockets with external power supply on the agenda for the day.

The analysis of the formulas presented here led K. E. Tsiolkovskiy to the idea of space trains. Various versions of connection of rockets were studied: sequential, parallel and combined; the so-called "second type" of compound rocket of Tsiolkovskiy called for parallel connection of rockets in groups. We know that all modern spacecraft booster rockets are multistage rockets, with both sequentially and simultaneously operating motors considered the most favorable combination.

Suggestions for LRE Fuels

Analyzing the properties of fuels, K. E. Tsiolkovskiy wrote, "They should perform the maximum work per unit of mass during combustion." And further, "For a reaction apparatus, the greatest possible portion of the thermal or chemical energy of the particles must be converted to coordinated motion of the particles."[1]

In his work, "Investigation of Space with Rocket Devices," K. E. Tsiolkovskiy in 1903 suggested liquid oxygen and hydrogen as fuel components for LRE. "At the present time, the conversion of hydrogen and oxygen to liquids represents no great difficulty. Hydrogen could be replaced by liquid or condensed hydrocarbons, such as acetylene or petroleum."[2] /32

In this same work, the scientist studies certain inorganic compounds as possible fuels. "For example, silicon, burning in oxygen ($Si + O_2 = SiO_2$), liberates a tremendous quantity of heat, 3654 cal per unit of mass of product produced (SiO_2), but unfortunately forms substances which volatilize with great difficulty."[3] K. E. Tsiolkovskiy gave great attention to the study of the fuel consisting of liquid oxygen and hydrogen. "Accepting liquid oxygen and hydrogen as the material most suitable for explosion..." he wrote in the work just mentioned. However, the scientist was bothered by the low density of hydrogen, requiring large containers, which would require an increase in the volume and mass of the rocket. In 1927, in the work "A Space Rocket. Experimental Preparation," he noted, "Liquid hydrogen is generally unsuitable, particularly for the first time. Reasons: high cost, low temperature, heat of evaporation, difficulty of storage."[4]

In 1903, he wrote, "...the quantity of energy per unit mass of the products of a compound depends on the atomic weights of the simple substances combined: the lower the atomic weight of these elements, the greater the heat liberated as they are combined."[5]

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 79.

[2] Ibid., p. 81.

[3] Ibid.

[4] Ibid., p. 270.

[5] Ibid., p. 81.

In 1914, K. E. Tsiolkovskiy suggested that ozone and other components be used as oxidizers in engines. "We must find compounds of hydrogen with carbon which contain the greatest possible quantities of hydrogen, which are formed as they are produced of elements with absorption of heat, for example acetylene, which, unfortunately contains little hydrogen. In this latter respect, turpentine is more suitable, and methane or swamp gas is still more suitable; this last substance is unfavorable in that it is difficult to liquify."[1]

In his work "The Investigation of Space with Reaction Devices," 1926 edition, K. E. Tsiolkovskiy compares hydrogen with hydrocarbons: "It is difficult to liquify and store, since unless particular precautions are taken it evaporates rapidly. Most preferable are liquid or easily liquefied hydrocarbons. /33
The more volatile they are, the more hydrogen they contain and the more suitable they are for the business at hand. Oxygen is tolerable in liquid form, particularly since it can serve as a source of cooling..." Further, the scientist notes, "But it is most suitable to work as follows: store most of the reserve of oxygen on-board in the form of one of its endogenic compounds, i.e., those which are synthesized (made up) with absorption of the material."[2]

In this same work, in 1926, methane, benzene and oil are recommended as fuels. In 1927, liquid air was recommended as an oxidizer: "Initially, liquid air can be used. The nitrogen present will weaken the explosion and decrease the maximum temperature."[3] The idea of using high-boiling oxygen-containing compounds was set forth by K. E. Tsiolkovskiy repeatedly. He also noted the expediency of using hydrocarbon compounds as the fuel. He considered the use of such fuels in his work "A Space Rocket. Experimental Preparation," of 1927. In his work, "Reaching the Stratosphere. A Fuel for a Rocket,"[4] He presents and analysis of the influence of the quality of fuel on the exhaust velocity of gases from the nozzle and the flight velocity of a rocket. Here, in particular, Konstantin Eduardovich wrote, "It is most suitable to replace oxygen with NO_2. This is a brown, chemically stable liquid, denser than water."[5]

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 145.

[2] Ibid., p. 243.

[3] Ibid.

[4] Manuscript received Osoviakhim Central Council in 1934.

[5] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 373.

Konstantin Eduardovich did not limit himself to the study of the possibilities for the use of liquid fuel components alone. In his work, "A Space Rocket. Experimental Preparation," he spoke of the possibility of using solid substances as fuels and suggested, in particular, carbon powder.[1] Although this type of fuel is not used in LRE at the moment, the idea of the use of powdered products and components in various states has been applied to some extent.

Konstantin Eduardovich was not fully satisfied by the energy qualities of chemical fuels. He presents a number of considerations concerning the possibility of using nuclear fuel. /34

In 1912, he wrote, "Therefore, if it were possible to accelerate the decomposition of radium or other radioactive substances sufficiently, this could provide, with otherwise equivalent conditions, sufficient velocity to a rocket that it could reach the furthest sun (star) in ten to forty years."[2] And again, "If radium, giving up its energy a million times more rapidly than occurs presently, could be used, interplanetary flights would be possible."[3] Later, in 1926, the scientist wrote, "The splitting of atoms is a source of tremendous power... This energy is 400,000 times greater than the most powerful chemical energy."[4]

However, at that time it was impossible to plan on the use of artificial radioactive isotopes and the use of fission or synthesis reactions.

In his work "The Investigation of Space with Reaction Devices" (1926), K. E. Tsiolkovskiy convincingly showed the undesirability of using artificial radioactive isotopes as a source of power. However, in this same work he wrote, "But we cannot be sure than inexpensive, rapidly fissioning sources of energy will not be found in time."[5]

Now, when artificial radioactive isotopes are produced easily, when spacecraft carry reaction engines which produce energy by the decomposition of artificial isotopes, the

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 262.

[2] Ibid., p. 136.

[3] Ibid., p. 143

[4] Ibid., p. 189.

[5] Ibid.

scientific forethought of K. E. Tsiolkovskiy on the possibility of acceleration of the splitting of isotopes is receiving its deserved attention.

Artificial radioactivity is the radioactivity of artificially produced atomic nuclei. Some artificial isotopes have short halflives, which allows significant power to be produced with these substances.

Current experimental models of radioisotope rocket engines utilize the energy of the decomposition of artificial radioactive isotopes, such chemical examples as polonium-210, strontium-90, plutonium 238, etc. The possibility cannot be excluded of the production and realization of the energy of extremely short lived isotopes directly on-board a spacecraft.

K. E. Tsiolkovskiy stated in 1912 the idea of the possibility of creation of electric rocket engines: "Possibly electricity might in time be used to attain a tremendous velocity in the particles ejected from a reaction device."[1] At the present time, electric rocket engines of various types are in use. Modern radioisotope and electric rocket engines develop low thrust and are designed for installation on spacecraft. /35

Konstantin Eduardovich studied a large group of chemical oxidizers and fuels for LRE, noted the possibility of using radioactive isotopes and electric power. In his works, he laid the foundations of the science of fuels for rocket engines.

Recommendations for the Design of Combustion Chambers

During the years when K. E. Tsiolkovskiy worked on problems of the theory of rocket and engines, it was difficult to imagine the design of a combustion chamber and produce any sort of precise idea of the processes occurring within it. General machine building did not have a single device in any was similar in its operating mode or magnitude of thermal and dynamic loads to an LRE combustion chamber. The design of this new thermal engine had to be developed, determining the nature and mode of its operation, analyzing the peculiarities of the design of the individual elements and selecting the structureal materials to be used.

From one question, K. E. Tsiolkovskiy went over to another, then, after achieving a solution, he returned to earlier problems, continuing deeper studies, considering the results produced earlier.

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[1]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 36.

Let us see how Konstantin Eduardovich imagined the design of a combustion chamber, which he called the "explosive" chamber. In his work "Investigation of Space with Reaction Devices" (1903), K. E. Tsiolkovskiy, speaking of the rocket, noted that it "...has a great reserve of substances which, when mixed, immediately form an explosive mass. These substances, regularly and evenly exploding in the place set aside for it, flow in the form of hot gases through tubes expanding toward their ends..."[1] /36

K. E. Tsiolkovskiy described the burning of the fuel as follows, "In essence there is no sharp difference between the process of explosion of a substance and simple combustion. Actually, both amount to more or less rapid chemical combination. Combustion is slower combination, explosion is rapid combustion."[2]

K. E. Tsiolkovskiy wrote of the possibility of controlling the motion of a rocket by changing the thrust vector as follows: "We see a rudder serving to control the motion of the rocket."[3] This suggestion of Tsiolkovskiy was practically realized in the form of gas rudders, as used presently to control the flight of a number of Soviet geophysical and other rockets. K. E. Tsiolkovskiy also suggested another means of controlling flight. He wrote: "Finally, by rotating the end of the tube, we could also keep our vehicle moving in the proper direction."[4] These These methods were studied by designers. Some modern rockets control the thrust vector by rotation of the primary combustion chamber or with control engines as, for example, on the booster rocket of the Vostok spacecraft.

Thermal and thermodynamic calculations, i.e., calculations of the thermal processes of conversion of the working fluid in the combustion chamber and in the nozzle of the reaction engine, performed by K. E. Tsiolkovskiy, noted the necessity of cooling the walls of the combustion chamber. As one version of cooling, he suggested a circulating system: "...the circulation of a metallic liquid in the air surrounding the tube is necessary for another purpose: to maintain an even, low temperature of the tube, i.e., to retain its strength."[5] To assure reliable protection of the chamber, Konstantin Eduardovich recommended that refractory insulating coverings be used: "... the inner portion

[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 73.
[2] Ibid., p. 368.
[3] Ibid., p. 74.
[4] Ibid., p. 75.
[5] Ibid., p. 79.

of the tube will be covered with some sort of special refractory material: carbon, tungsten... Some metals are made stronger by cooling; these are the sort of metals which must be used, for example copper."[1] In 1911, in the work "Investigation of Space with Reaction Devices. The Reaction Rocket of K. E. Tsiolkovskiy," he discussed the need to cool the combustion chamber, the "explosion tube," with liquid hydrogen and oxygen. /37

The scientist imagined a system of internal and external cooling with both components as follows: "Furthermore, the tube is continually cooled on both the outside and inside. Actually, a continuous stream of two very cold liquids is sprayed into the initial section of the tube: liquid oxygen and oil cooled by the liquid oxygen. The outer walls of the tube are cooled by the cold oil, which itself is cooled by the liquid oxygen which surrounds it."[2]

K. E. Tsiolkovskiy emphasized that iron could not be used to make the nozzle. He stated that more refractory materials were required, for example tungsten: "It does not seem impossible to find materials which could withstand this temperature. Here are a few of the melting points of materials known to me: nickel -- 1500, iron -- 1700, indium -- 1760, paladium -- 1800, platinum -- 2100, iridium -- 2200, osmium -- 2500, tungsten -- 3200, while carbon does not melt even at 3500° C."[3]

The recommendations of Konstantin Eduardovich for the design of the combustion chamber and selection of materials to assure a normal thermal operating mode of the walls are interesting. "The explosion tube should be made of a material which is strong (even at high temperatures), refractory and non-flammable; it would also be good for it to be a good heat conductor. It seems most favorable to make the tube of two envelopes: the first -- inner envelope -- of a less refractory but strong, good conducting material."[4] And again, "It would be useful to cover the steel tube with a layer of a metal which conducts heat well, for example cuprite, aluminum and others (for better cooling of the tube)."[5] Copper-based alloys have been very widely used in domestic rocket engine construction. /38

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 79.

[2] Ibid., p. 271.

[3] Ibid., p. 133.

[4] Ibid., p. 263.

[5] Ibid., p. 272.

Other works of K. E. Tsiolkovskiy are known, dedicated to the problems of design and reliable operation of the combustion chamber of a rocket engine, as well as the selection of materials to assure normal thermal mode of the walls.

Many of the ideas of K. E. Tsiolkovskiy have been used in the design of modern LRE; in particular, they almost all have external cooling with the oxidizer or fuel, and internal cooling is also used. For example, the engines of the V2A, V5V geophysical rockets, the RD-107, RD-119 and other engines have inner walls cooled by enrichment of the combustion products with fuels in the layers near the walls and by the use of natural flow-through cooling. The heat liberated from the walls is returned to the combustion chamber. This method of cooling is called regenerative; it was also suggested by K. E. Tsiolkovskiy. Materials with high heat conductivity, highly refractory and with good strength characteristics are currently used to manufacture combustion chambers.

Thus, K. E. Tsiolkovskiy, in order to assure a reliable thermal mode of the combustion chamber wall, suggested that high strength, thermally stable materials be used, that the steel wall be clad with copper, that copper be used as a structural material, that the chamber be equipped with a heat insulating refractory liner and that the outside be cooled by flowing fuel components or a circulating system with liquid metal, that the heat flux from the gases to the wall be reduced by means of internal cooling.

Modern methods of investigation of LRE cooling systems have also led to recommendations quite similar to those of K. E. Tsiolkovskiy.

Let us take for example a chamber with external flowing coolant. Let us assume that the inner surface of the wall is heated by convection. In order to increase the permissible temperature of the inner surface of the chamber wall, high-strength, thermally stable materials should be used. To decrease the wall temperature, the heat conductivity of the wall material should be increased, which is possible if copper or copper alloys are used, if the external cooling is intensified by increasing the heat transfer coefficient from the wall to the fluid. This is achieved by selecting a liquid with optimal cooling properties, by increasing the flow rate of cooling fluid per second, which is possible if a circulating cooling system is used. The wall temperature can also be reduced by decreasing the heat transfer factor from the gases to the wall (using the principle of internal cooling). The temperature of the gases in the layer next to the wall is decreased in this case, also leading to a decrease in the temperature of the wall. /39

Tsiolkovskiy published the first results of thermochemical calculations in 1903, presenting data on the thermal effect of combustion of hydrogen and oxygen. In 1914, in the work "Investigation of Space with Rocket Devices," he spoke of the determination of the temperature of the combustion products considering dissociation. Consideration of dissociation allows more precise determination of the value of the thermodynamic parameters, the most proper approach to analysis of structural elements. Based on nonrelationships, he calculated the instantaneous values of the temperature of the expanding gas stream. In 1926, his calculations were continued to the point of determination of the parameters of the gas and the efficiency of the engine depending on the degree of expansion of the gases in the nozzle.

Analyzing the operating conditions of a combustion chamber, K. E. Tsiolkovskiy concluded that its weight and volume would be low. In his work "A Space Ship," written in 1924, the combustion chamber is described as follows: "Only this chamber and its continuation -- the explosion tube, into which the products of the explosion will flow, gradually expanding and cooling due to the conversion of disordered thermal energy into kinetic energy -- will experience the pressure of the gases... The tubes and explosion chamber are very low in volume."[1]

In 1926, in his work "Investigation of Space with Reaction Devices," comparing possible modes of operation of chambers, he wrote "the pressure of the explosive substances can be varied from 5,000 atm to a desirable lower value." And again, "The mixing may be so complete, so close, that the explosion will be almost instantaneous or, conversely, it can be as slow as combustion..."[2] /40

Studying the operation of a combustion chamber in its interaction with the fuel feed system, the scientist comes to the conclusion of the necessity to limit the pressure in the chamber: "We can now indicate the required minimum pressure." And the conclusion, "In any case, we can limit ourselves to 100 atm."[3]

In the work just cited, Tsiolkovskiy describes the process of conversion of heat, liberated on combustion of the

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 164.

[2] Ibid., p. 201.

[3] Ibid., p. 202.

fuel, to kinetic energy in the gas stream and presents the results of his calculations.

In this same work, the peculiarities of the design of some parts of the rocket and its engine are noted. As concerns the nozzle, the following statements were made: "However, the greater its angle, the greater the loss of energy, since the motion of the gases is deflected to the side. Still, with an angle of 10°, the losses are almost unnoticeable."[1] However, in 1927, he recommends that the optimal value of the angle of expansion of the nozzle be determined by experimentation.

In 1927, in the work "A Space Rocket. Experimental Preparation," the method of injection of fuel to the chamber and its preparation for combustion is described as follows: "...gratings with slanted holes for better mixing of the hydrocarbon with the oxygen mixture. The beginning of the explosion tube is divided by a channel. Along one half flows the oxygen mixture, along the other half -- the hydrocarbon."[2]

Development of Feed Systems

The plan of the system which feeds fuel to the chamber of the rocket engine was developed by K. E. Tsiolkovskiy in 1903. In his work "The Investigation of Space with Reaction Devices," K. E. Tsiolkovskiy suggested and himself described a system of fuel feed with unloaded tanks, i.e., tanks in which the fuel is stored under low pressure.

At first, considering that there would be very high pressures in the combustion chamber, K. E. Tsiolkovskiy concluded that it would be necessary to use a pulsed fuel flow mode. In 1914, he wrote, "Ordinary types of pumping should not be used. It would be simplest of all to place a certain charge in the tube and allow it to burn and fly out. Then, when the pressure in the tube had dropped, another charge would be injected, etc."[3] Here also he stated the idea of the possibility of using a gas-jet ejector: "There should be a branch at the very mouth of the tube, through which the gases would be returned once more to the mouth and, due to their velocity, entrain and force the explosive material in a continuous stream

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 247.

[2] Ibid., p. 263.

[3] Ibid., p. 147.

into the very mouth of the explosion tube."[1]

Analysis of the weight qualities of the feed system led the scientist to the idea of the need to reduce the pressure in the chamber, to select its optimal value. "At high pressure," Konstantin Eduardovich wrote in 1926, "the use of the energy is great, but impossibly great work is required to force the masses into the explosion tube. Therefore, the maximum pressure in the tube should be reduced as greatly as possible, without losing efficiency."[2]

The idea of pulsating feed was formulated by him as follows: "...it could be made so that the pressure at the beginning of the tube varied periodically, for example, from 200 atm to 0 and from 0 back to 200 atm. The variation would occur in waves."[3]

K. E. Tsiolkovskiy believed that the walls of the tank should also form the shell of the rocket. "The main shell of the rocket," Konstantin Eduardovich wrote in 1926, "should withstand without danger a pressure of at least 0.2 atm, if filled with liquid oxygen."[4] "Then, to store them (i.e., the fuel components) ordinary tanks or even the rocket itself could be used."[5] These rockets have been widely used. Thus, K. E. Tsiolkovskiy suggested to so-called "load-bearing tanks," i.e., fuel tanks, the side surface of which is at the same time the outer shell of the fuel section, receiving external longitudinal forces and bending moments acting on the section. The use of load-bearing tanks allows the mass of a rocket to be greatly reduced in many cases.

In 1927, the scientist suggested that a pumping unit be installed between the tanks and the chamber: "... -- two pumps, driven by a common motor. The first pumps the oxygen compounds into the explosion tube, the second -- the hydrogen compounds."[6] Calculations have shown that the fuel consumption for the pump drive would be insignificant: "...the motor would use several hundred times less fuel than the explosion tube."[7] /42

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[1] Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, pp. 147-148.

[2] Ibid., p. 201.

[3] Ibid., p. 202.

[4] Ibid., p. 243.

[5] Ibid., p. 246.

[6] Ibid., p. 261.

[7] Ibid., p. 265.

As a result of his studies of the peculiarities and conditions of operation of individual units and systems of the rocket, in 1927, in his work "A Space Rocket. Experimental Preparation," K. E. Tsiolkovskiy presented a description of the launch and operation of the motor in flight.

Konstantin Eduardovich Tsiolkovskiy was an outstanding researcher, whose scientific activity was unusually broad. He made many discoveries in the area of rocket dynamics, aerodynamics, the theory of aviation, the theory of interplanetary voyages, the theory of engines, etc. The work on rockets performed by K. E. Tsiolkovskiy, did not amount to a completed technical plan. We can gain an idea of his design only by looking at his calculations and descriptions.

The most important thing in the works of Tsiolkovskiy was the proof of the possibility of constructing a large space rocket with an LRE, confirmed by calculations. K. E. Tsiolkovskiy pointed the way into space. Soviet and foreign scientists recognize the priority of Tsiolkovskiy as the founder of theoretical astronautics. The name of Tsiolkovskiy has been given to a crater on the far side of the moon. Konstantin Eduardovich Tsiolkovskiy is recognized as the head of a new trend in science and technology -- astronautics and rocket building.

In connection with the launch of the world's first artificial satellites, a gold "Tsiolkovskiy Medal" was founded, awarded by the Academy of Sciences USSR for outstanding work in the area of interplanetary voyages. In 1958, the first medal was awarded to the Chief Designer for Rockets and Spacecraft, Academician Sergey Pavlovich Korolev, while the second medal was awarded to the Chief Designer of Rocket Engines.

1.4. One of the Pioneers of Rocket Technology, Yu. V. Kondratyuk /43

The attempts of historians to write a detailed biography of Yu. V. Kondratyuk, a talented and gifted man, a remarkable scientist, mechanic and inventor, and the author of the well-known works "Mastern of Interplanetary Space" and "Those Who Will Read in Order to Build," have not yet been fully successful. Too few documents have been retained in the archives.

Yu. Vasil'yevich Kondratyuk was born in 1897 in the Ukraine, in the city of Poltava. The unfortunate conditions of his life did not allow him to complete his education: Yu. V. Kondratyuk worked as a hired laborer, chopped firewood, and worked as a lubricator and mechanic at mills. He studied

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mathematics, physics and chemistry independently. In his youth, Yu. V. Kondratyuk became interested in the theory of interplanetary voyages. In 1918, looking over some old magazines, he came upon one of the articles of K. E. Tsiolkovskiy on his stratoplane, while he read the other works of Tsiolkovskiy, particularly his article "The Investigation of Space with Reaction Devices" (which was written in 1911) only in 1925.

The basic problems and physical principles of interplanetary flights were set forth by Yu. V. Kondratyuk in his work "Those Who Will Read in Order to Build," the work on this manuscript was begun in 1916 and completed in 1919. This work of Yuriy Vasil'yevic was first published in 1964. Based on his own studies and his familiarity with some of the works of K. E. Tsiolkovskiy, Yu. V. Kondratyuk reworked this article several times. He performed careful studies of a number of rocket and space problems, presented new solutions and performed many calculations. /44

Yuriy Vasil'yevich Kondratyuk

Yu. V. Kondratyuk produced the basic equation of motion of a rocket by his own original method independently of K. E. Tsiolkovskiy, with the works of whom he became familiar only later.

In 1925, the manuscript of "Mastery of Interplanetary Space" was sent to Professor V. P. Vetchinkin (1885-1950), who made a positive response.

Encouraged by success, Yu. V. Kondratyuk continued his studies and in 1929 published the manuscript in Novosibirsk, edited by Professor V. P. Vetchinkin. In the foreword to the book, Vladimir Petrovich wrote the following on 4 December 1927: "The book by Yu. V. Kondratyuk which you hold is doubtless the most complete study of interplanetary voyages written in the Russian and foreign literature up to the present time. All the studies were performed by the author quite independently. This book discusses with exhaustive completeness all problems encountered in other works and, furthermore, presents the solution to a number of new problems of primary importance, not mentioned by other authors. These problems include:

"The suggestion that solid fuels (lithium, boron, aluminum, magnesium, silicon) be used in addition to gaseous fuels, both to increase the heat of combustion, and in order to use

combustible tanks which, after they are emptied of liquid fuel, are themselves processed and sent to the furnace. This same suggestion was made by engineer F. A. Tsander in a report at the Theoretical Section of the Moscow Society of Astronomy Enthusiasts in December of 1923, but this suggestion was included in the manuscript of Yu. V. Kondratyuk before the report of Tsander.

"He first presented a formula considering the influence of /45
the weight of the tanks for fuel and oxygen (proportional passive to use the terminology of the author) on the total weight of the rocket, and proved that a rocket which did not jettison or burn its tanks during flight could not escape the bonds of the Earth's gravity.

"He also first made the suggestion to make a rocket with wings and fly it in the air like an airplane. This suggestion has not appeared in the foreign literature at all (it being rather suggested that parachutes be used to return the rocket to the Earth), while Russian works have seen this suggestion, stated by F. A. Tsander at the same meeting and later printed by K. E. Tsiolkovskiy, but only after it appeared in the manuscript of the author. However, the studies of Yu. V. Kondratyuk go further, since he not only indicates the need for the use of wings, but also presents a rather detailed study as to the accelerations at which wings will be useful, the trajectory angles of the rocket to the horizon for the use of wings, and gives the most favorable force of reaction of the rocket during flight in the air; it is found to be on the same order as the initial weight of the rocket.

"Generally, the dynamics of the takeoff of the rocket repre-ent the most difficult portion of the problem, and Yu. V. Kondratyuk has solved it more completely than any other author.

"Here also is presented a study of the heating of the foreward portion of the rocket by the air considering both adiabatic compression of the air, and radiation of the surface of the rocket and of the heated air itself. This problem was also studied by no one.

"All numbers were given by Yu. V. Kondratyuk, although rather roughly (which he himself mentions in the foreword), but always with his error in the direction unfavorable to the designer.

"This book can serve as a desk reference book for all those involved in problems of rocket flight."

In the early 1930's, Yu. V. Kondratyuk, without interrupting his work on rocket technology, began studying high power wing installations. Supported by the People's Committee for Heavy Industry and TsAGI, he headed the planning of a wind power plant

at the Ukrainian Scientific Research Institute for Industrial Power Engineering (Khar'kov). The plan was approved by the Academy of Sciences USSR. To bring it to life, "Teploenergostroy" Trust (Moscow) was directed to construct a wind power plant with a capacity of 12,000 kw in the Crimea, under the leadership of G. K. Ordzhonikidze. In 1938, Kondratyuk was named Chief of the Technical Section of "Teploenergostroy" Trust, then Chief of the Planning Section of the "Planning and Experimental Office for Electric Power Plants." In later years, Yu. V. Kondratyuk studied the construction of powerful wind power plants, as before without interrupting his studies on interplanetary voyages. /46

In 1947, the book of Yu. V. Kondratyuk "Mastery of Interplanetary Space" was reissued. Some of the conclusions of Yu. V. Kondratyuk agreed to some extent with those made by K. E. Tsiolkovskiy. However, Kondratyuk's book contained a great deal of new and original material. The young scientist was the first to develop: the energetically most favorable trajectories for space flights, problems of the theory of multistage rockets, designs for intermediate filling stations on the artificial satellites of the planets, particularly the moon, the conditions for economical landing of rockets on the Earth using atmospheric braking, approximate methods of calculation of the heating of a rocket as it moves through the atmosphere. He recommended that a number of types of oxidizers be used, particularly ozone, while recommending metals, metalloids and their hydrogen compounds such as boron hydrides as fuels. After suggesting that winged rockets be used, Yu. V. Kondratyuk indicated the areas of their application and performed studies on the selection of the most suitable aerodynamic characteristics.

Our attention is drawn to the idea of Yu. V. Kondratyuk of the utilization of solar energy: solar heat is converted by electricity, then thrust is created by expulsion of elementary particles.

On 7 June 1941, Yu. V. Kondratyuk enlisted in the People's Volunteer Core. Leaving for the front, he gave his friends a suitcase and portfolio with his manuscripts for safekeeping.

Yu. V. Kondratyuk was a soldier in the Communications Company of the 2nd Regiment of the People's Militia Division of the Kiev Region of Moscow. He took part in battles with the German Fascist invaders and died at the front in 1942.

The name of Kondratyuk has been given to a crater on the far side of the moon.

The Works of Yu. V. Kondratyuk on Rocket Engines

Like K. E. Tsiolkovskiy, Yu. V. Kondratyuk came to the conclusion that rockets should be driven by LRE and should have more than one stage. In his book "Mastery of Interplanetary Space," he wrote that the reserve of energy to be used to impart speed to a flight vehicle can be carried on board in quite varied forms, but that only the chemical energy of the compounds of certain substances would be sufficient to allow flight in practice. Planning on the use of a multistage rocket, Yu. V. Kondratyuk objectively studied its design, flight conditions and provided a foundation for the selection of fuels, suggesting an arrangement of the combustion chamber and nozzle and indicating the need to use a turbine pump unit. /47

Suggestions for LRE Fuels

In selecting a fuel, Yu. V. Kondratyuk first turned his attention to its efficiency. Furthermore, he believed it necessary to consider all of the variety of properties of a fuel, as well as the design of the rocket and the specifics of the conditions of its use. If the rocket is composite, i.e., a multistage rocket, a greater quantity of fuel is required for the operation of the first stages than for the latter stages.

In selection of fuel, Yu. V. Kondratyuk noted, one must also turn attention to its cost. According to Kondratyuk, the use of the least expensive fuels would be expedient for the first stages of the rocket, with more efficient and costly fuels to be used in later stages. Kondratyuk suggested a formula considering the cost of the fuel, its mass and thermal efficiency to estimate the "cost of reaction."

He considered liquid air, oxygen and ozone to be the most effective oxidizers, with petroleum products, liquid acetylene, methane-based fuel, hydrogen and its compounds, as well as products containing aluminum, magnesium, silicon and boron to be the best fuels. The last fuel could be used as an amorphous powder, pulverized in the combustion chamber by a stream of hydrogen or methane or added to oil before it was fed into the combustion chamber. Yu. V. Kondratyuk suggested boron hydride as a fuel. /48

Yu. V. Kondratyuk studied several groups of fuels: first, liquid air-petroleum or liquid oxygen-petroleum, then liquid acetylene, then liquid hydrogen. He then studied the possibility of using several metalloids and metals. Kondratyuk calculated the thermal effect of a variety of fuels, as well as their combustion product exhaust velocity from the nozzle and other

parameters. Kondratyuk stated his doubts concerning the expediency of using liquid hydrogen, due to its low density.

Recommendations for the Design of the Combustion Chamber

Kondratyuk turned a good deal of attention to problems of the organization of combustion in LRE combustion chambers. As early as 1918-1919, studying the combustion of hydrogen and oxygen, he wrote that the combustion of the fuel could be organized by three methods -- either a prepared mixture could be ignited, or the gases need not be mixed until the actual moment of ignition, or they would be only partially mixed, with the best method to be determined by experience.

To assure completeness of combustion, Kondratyuk suggested a checkerboard placement of the fuel component sprayers in the spray head of the combustion chamber. He also suggested a "stratified" version. In this case, the sprayers would be placed along walls of the chamber in belts, alternating with each other. In his thermodynamic calculations, Yu. V. Kondratyuk considered the dissociation of the combustion products; he believed that the process in the chamber is nearly isothermal, while adiabatic expansion of the gases occurs in the nozzle.

According to Yu. V. Kondratyuk, the "combustion chamber" and "expulsion tube," i.e., the nozzle, should be made in one piece, and he believed that the surfaces exposed to gases at temperatures higher than those which could be withstood by the refractory material applied to the walls of the chamber, should be made of metal -- copper or one of the refractory metals (chromium or vanadium), and that the walls should be intensively cooled on the inside by liquid gases fed into the combustion chamber. /49

Studying the design of the nozzle, Yu. V. Kondratyuk wrote that the most favorable nozzle shape approximates a paraboloid of rotation, but not a quadratic paraboloid, rather one of higher order; toward the nozzle exit plane, it should be converted to a cylinder. The flow of combustion products leaving the nozzle would then by one dimensional, not diverging, in order to achieve the greatest possible efficiency and, consequently, thrust. Yu. V. Kondratyuk pointed out that the finish of the inner surface of the nozzle should be such as to provide the minimum loss due to friction of the combustion products against the wall, and that the profiling of the nozzle and calculation of cross sections should be based on the condition of conservation of constant flow rate (continuity of flow) of the combustion products.

Studying the influence of external conditions on the operation of an LRE, Yu. V. Kondratyuk recommended that, in order to avoid decreasing the efficiency as the engine operated at low altitudes, the cross-sectional area be decreased, i.e., the nozzles should be equipped with an additional device in the form of a constricting cone at the exit plane of the nozzle, to be used in the lower layers of the atmosphere then jettisoned as the altitude increased. As another version of thrust regulation with altitude, he suggested that the combustion chamber be equipped with a dual nozzle -- the first to provide optimal parameters for operation at low altitude, the second to be used at high altitude and to begin operation after the first nozzle is jettisoned.

Many of the suggestions of Yu. V. Kondratyuk concerning the design of combustion chambers have been realized in practice.

Development of Feed Systems

In his work "Those Who Read in Order to Build," he noted that a rocket engine with a chemical source of energy should consist of vessels, tanks, the combustion chamber tube and devices to feed the fuel components from the tanks to the combustion chamber of the rocket engine. Yu. V. Kondratyuk suggested that pump systems be used to feed both single-component and two-component fuels. At first, he planned on the use of piston pumps. Later, he wrote that pumps could also be made pistonless. /50
Kondratyuk's pumps were to be single-cycle pumps, and each component was to have its own pump. The liquefied gases fed by the pumps were to be used primarily for combustion, partially to pressurize the tanks carrying the fuel components.

To assure normal operation of the engine, Kondratyuk suggested a fuel-feed regulation system. The sensing element used was a device similar to an aneroid barometer, reacting to the pressure difference inside and outside the tanks.

The actuating element regulating the tank pressurizing system is a choke valve installed before the inlet for gas products into the tank. Yu. V. Kondratyuk also suggested that a mixture quality regulator be installed before the inlet to the combustion chamber, although the introduction of the regulation system complicates the design of the engine.

Furthermore, Yu. V. Kondratyuk turned particular attention to the need for preliminary development and experimental checking of the elements of the engine. Thus, Yu. V. Kondratyuk suggested methods of assuring the required operating mode of the engine by its adjustment to a fixed mode and regulation during operation, now used in practice.

Kondratyuk recommended that an internal combustion engine or turbine powered by the main components of the fuel be used as pump drives; the use of oxyhydrogen gas was studied.

Kondratyuk made a great contribution to the science of LRE and rockets. A number of problems of rocket dynamics and engine construction were solved uniquely by him, as was noted above. In particular, in developing methods for the production of the energetically most suitable trajectories for space flights, Kondratyuk suggested that a flight to the moon and the planets be made by putting artificial satellites in orbit around them, with subsequent separation of a landing and takeoff spacecraft, the system used by the Apollo flights. He also suggested that the fields of gravity of heavenly bodies by used to accelerate or decelerate spacecraft.

1.5. The Scientist and Inventor F. A. Tsander

Fridrikh Arturovich Tsander, a talented enginee, was one of the pioneers of Soviet rocket construction and an enthusiast for interplanetary flight. /51

Fridrikh Arturovich Tsander (1913 Photo)

F. A. Tsander was born on 11 August 1887 at Riga. In 1906, he successfully completed the secondary school. "During my last year at this school," F. A. Tsander wrote, "before the winter holidays, our cosmography teacher read us a part of an article written by K. E. Tsiolkovskiy in 1903, entitled 'Investigation of Space with Reaction Devices.'"[1] In 1907, Fridrikh Arturovich entered the Mechanical Department of Riga Polytechnical Institute, from which he graduated with honor in 1914, and was named an Engineer-Technologist.

Fridrikh Arturovich became interested in rocket technology during his student years. "In 1908," he wrote, "when I was 21, I began to keep a special notebook for the design of spaceships; although I knew as yet very

[1] Autobiography of F. A. Tsander, family archives.

little, under the influence of my calculations I had already begun to hope for the possibility of flights in space."[1] In 1909, F. A. Tsander was an initiator in the creation in the Institute of the "Second Riga Student's Society for Air Travel and Flight Technology," and in that same year he constructed a glider with his comrades. /52

F. A. Tsander advanced from the idea of reaching great altitudes by means of an airplane and propeller motor to the idea of the possibility of interplanetary space flight with a rocket engine. In order to attempt to realize his plans, F. A. Tsander began work at Moscow Aviation Plant No. 4, "Motor" in February of 1919 as the head of the technical bureau. Late in 1921, F. A. Tsander presented to the Moscow Governor's Conference of Inventors a plan for an engine for an interplanetary airplane-spaceship. From June 1922 through July 1923, Tsander, on temporary leave from the plant, worked at home. He constantly felt the support of the workers, who gave him significant material assistance. F. A. Tsander valued this relationship, and reported to the workers. For example, in April of 1923, at a plantwide meeting of workers of "Motor" Plant, he reported his hope to be able to give his plan to the plant for construction.

In 1924, in the journal "Tekhnika i Zhizn'", No. 13, the first printed work of F. A. Tsander appeared -- the article "Flights to Other Planets." In this article, he presented his basic idea -- the combination of a rocket with an airplane, with subsequent burning of the metal parts of the airplane. In 1924, F. A. Tsander wrote the article "Description of the Interplanetary Spaceship-Airplane System of Tsander," which was sent to the Committee for Inventions of the All-Russian Council of the National Economy 8 July 1924. This article was published in the collection "Raketnaya Tekhnika" [Rocket Technology] in 1937. F. A. Tsander believed that an airplane with a piston engine could achieve an altitude of about 28 km and a speed of 350 to 450 m/sec. After this, the ship is switched from the piston engine to a rocket engine. No longer needed, the airplane is pulled piece by piece (wings, tail, chassis, piston engine, etc.) into a special device, where it is melted and used as an additive to the liquid fuel. At the end of the acceleration run, at an altitude of 85 km, only the rocket with small rudders and wings as needed for a gliding descent would be left.

Attempting to get his works published, F. A. Tsander sent some of them, particularly "The Utility of Acceleration of the Flight of a Rocket at Moments when the Flight Velocity of the /53

[1] Autobiography of F. A. Tsander, family archives.

Rocket is Great," "Flights to Other Planets," and "Calculation of the Flight of an Interplanetary Ship in the Atmosphere" to the Scientific Council of the People's Commissariat for Education, RSFSR, Professor V. P. Vetchinkin. In his review of 8 February 1927, which was sent to the Scientific Department of the Main Administration for Science, V. P. Vetchinkin, noting the value of the ideas and works of F. A. Tsander, considered it quite necessary to help F. A. Tsander to prepare and publish his works, some chapters of which had already been presented to the Administration for Science, as rapidly as possible. Actually, due to the fact that the publication of scientific works was not given its proper significance, in those years we lost priority even in those cases when it factually and undisputably belonged to our country. For example, in 1925 the work of engineer Gochman was published abroad, in which he suggested flight on wings and gliding descent. The ideas developed by Yu. V. Kondratyuk and F. A. Tsander were published in this work.

A few days after he received a reply from V. P. Vetchinkin, F. A. Tsander sent the Scientific Division of the Main Administration for Science an announcement, in which he requested to be allowed to work at the Central Institute for Aerodynamics and Hydrodynamics (TsAGI) or the Aviation Trust exclusively in the area of interplanetary voyages, and permission to prepare for printing a book on interplanetary voyages. In July of 1927, the Administration sent a message that the request of F. A. Tsander was not approved.

In order to make his employment more closely related to the development of space flight, F. A. Tsander had earlier, in October of 1926, transferred to work at Aviation Plant No. 4 in the Central Design Bureau of the Aviation Trust as a Senior Engineer. F. A. Tsander reported the results of his works on problems of the theory of rocket engines in a report "Preliminary Work on the Construction of a Reaction Apparatus," which he read on 30 November 1928 at the 15th Session of the Commission on Scientific Air Travel of the Moscow Aerological Observatory. In 1929-1930, F. A. Tsander, at the request of the Aviation Trust, prepared a report on the basis of his studies entitled "Problems of Superaviation and Immediate Problems on the Preparation for Interplanetary Voyages" for the Fifth International Congress on Air Travel, which was planned for September of 1930 at the Hague. After a number of revisions of the material which formed /54
the basis of this report, F. A. Tsander prepared his book "The Problem of Flight with Reaction Apparatus," which was published in 1932.

In December of 1930, F. A. Tsander began to work at the Central Institute of Aviation Motor Building (TsIAM), where in 1931 he began the construction of the OR-1 aviation reaction engine, followed by the OR-2 LRE. The OR-1 engine operated on

compressed air (supplied from cylinders or by a compressor) and gasoline; the OR-2 LRE at first (in 1933) was tested with liquid oxygen and gasoline. We can trace the sequence of work in this direction in the diary of F. A. Tsander.

On 15 September 1931 in his diary he comments on his work on the airplane with the reaction engine; on 1 October, he discussed with Yu. A. Pobedonostsev "installation of the reaction engine on the airplane," and on 2 October he wrote in his diary "about the oil-oxygen rocket for the airplane"[1]; on 7 October he noted the conduct of the 32nd test of the OR-1, held in the presence of S. P. Korolev and other specialists, while on 19 October we see the first mention of the OR-2 engine; on 18 November 1931, F. A. Tsander concluded a Socialist contract with the Aviation Technology Bureau of the Scientific Research Sector of the Osoaviakhim CC for the planninf of a reaction engine, including its installation on an aircraft.[2]

F. A. Tsander agreed to plan and produce working drawings for the OR-2 reaction engine for the RP-1 jet aircraft in the following periods of time: combustion chamber with nozzle, tanks for fuel with safety valve, tank for gasoline -- by 25 November 1931; compensator for cooling of nozzle and heating of oxygen -- by 3 December 1931. The times for completion of calculation of the temperature in the combustion chamber, exhaust velocity and axial pressure of the jet in the nozzle at various pressures in space, weights of the parts, flight duration of the RP-1 reaction aircraft with various oxygen contents, calculation of the heating and cooling system, approximate calculation of the temperature of the walls of the combustion chamber -- all corresponded to the time for completion of the drawings.

Manufacture and testing of the nozzle and combustion chamber were planned for 2 December 1931; the fuel tanks for liquid oxygen and gasoline -- by 1 January 1932; installation of the OR-2 on the RP-1 aircraft and flight testing were planned for the end of 1932.

An addendum to the agreement noted that if the planned improved nozzle included a direct and reverse cone, calculations and drawings were to be completed by 15 January 1932. This extremely short period of time for completion of a complex problem of large volume, including theoretical study, calculation, /55

[1]F. A. Tsander family archives.

[2]Archives of Academy of Sciences USSR, F 573, d 269, p. 10.

planning, manufacture and testing, characterized both the enthusiasm and optimism of the contractor, and the underestimation of the difficulties which would arise in completing the obligations undertaken. This was a result of the lack of experience in development of LRE, as well as the mismatch between the complex technology of manufacture of the engine and the relatively low production capacities which could be found at the time.

In 1931, Osoaviakhim allocated F. A. Tsander 1000 rubles for the study of reaction motion, on 25 February 1932 another 13,000 rubles for the testing of rocket aircraft, followed by 80,000 rubles in March of the same year.

It soon became clear that the preparation of detailed working drawings and the completion of full calculations of a reaction engine with a complex control system were simply too much for F. A. Tsander alone. The need thus arose to concentrate the efforts of scientists and engineers working in the area of reaction technology.

F. A. Tsander also believed that for practical development of rocket technology, the largest possible number of engineering and technical workers, particularly talented young people, would be needed. We will discuss in detail the creation and development of the creative team headed by F. A. Tsander.

In 1932, Tsander's work "The Problem of Flight Using Reaction Apparatus" was published as a separate book. Here, in addition to the presentation in the theory of the flight of rockets and airplanes, we find methods of selection of fuel and design of various reaction engines.

In 1932, F. A. Tsander began working on the creation of his first LRE, called the OR-2. The engine was tested for the first time in 1933, burning liquid oxygen and gasoline. Later, at the RNII, the design of the engine was significantly changed in order to improve its efficiency, and in version 02 it used liquid oxygen and highly concentrated ethyl alcohol.

Liquid oxygen (like liquid fluorine, liquid hydrogen) is a cryogenic rocket fuel component. It is a compressed gas, cooled to a low (cryogenic) temperature. Cryogenic fuel must be used when this is justified by the increased specific impulse which it provides, for example in the boosters of spacecraft. Cryogenic fuel is not suitable for long-term storage, due to the evaporation losses.

At GIRD from the very first days of organization of this group and formation of the first team, Fridrikh Arturovich worked on other problems as well. He turned his attention to the construction of a rocket, later called the GIRD-X. Work was

begun on this rocket in January of 1933, and it was launched on 25 November of the same year, but without Tsander. The creation of the GIRD-X rocket was preceded by many calculations, rough plans and experiments, performed and conducted by Fridrikh Arturovich. /56

F. A. Tsander spent most of his day in calculation, while also working on production, helping the mechanics who encountered slight difficulties in the manufacture and tuning of apparatus new for the time. The engineers and designers, with F. A. Tsander as their chief, worked together in a small room. They worked morning, noon and night, whenever needed, as long as they had strength.

In addition to his plan tasks, F. A. Tsander calculated and thought about the design of individual units of the rocket, which he called a "spaceship."

"Forward to Mars!" "Faster to Mars" -- these words symbolized the goal of his life. He frequently shared his thoughts with his coworkers on the first team, tossing off drawings of individual parts of the spacecraft. Gradually, the form of the future rocket developed, the rocket which Tsander dreamed would fly to our neighbor planet.

During the last months of his life, Fridrikh Arturovich worked especially hard. As a result of overfatigue, systematic lack of sleep, poor and irregular feeding, F. A. Tsander began to lose his ability to work. On the insistance of his coworkers, Fridrikh Arturovich traveled to Kislovodsk for treatment. On the way, he contracted typhus and died on 28 March 1933.

In 1947 a collection of the works of F. A. Tsander was published under the title "The Problem of Flight Using Rocket Apparatus." The collection was reissued in 1961, expanded to include many works published for the first time.

The archives contain many more unpublished works of the scientist. Most of the remaining manuscripts require long and tedius work to translate Tsander's shorthand to ordinary text. The difficulty of decoding is explained by the fact that F. A. Tsander used a long-forgotten type of shorthand, which he himself altered somewhat, writing on specific problems of the theory of engines and rockets in German. Thus, the work with the manuscripts of F. A. Tsander requires specialists familiar with his system of writing, fluent in German and familiar with rocket technology.

The first deciphering of the works of F. A. Tsander was performed at RNII. In 1934, a group of stenographers under the direction of Ye. K. Moshkin decoded several notebooks filled

with writings recorded by F. A. Tsander during the early period of his activity. Up to 1960, the study of the heritage of F. A. Tsander was conducted with no strict plan, unsystematically. The appearance of earlier unpublished ideas of F. A. Tsander in print and the organization of a number of meetings, jubilees and conferences dedicated to the memory of F. A. Tsander are largely due to the efforts of Astra Fridrikhovna Tsander, the daughter of the scientist, who also prepared a collection of the works of F. A. Tsander "From his Scientific Heritage" for printing (Nauka Press, 196?). The documents in this collection, from the archives of Tsander, are interesting in many respects. In particular, it is noted here that Tsander began planning the OR-1 engine in 1928. A method of the calculation of "Hydrogen-Oxygen Rockets" is presented (April, 1927), in which the thermodynamic calculation of LRE is accurately explained. /57

Since 1965, the deciphering and study of the works of F. A. Tsander have been included in the plan of the Institute of the History of Natural Science and Technology of the Academy of Sciences, USSR.

In May of 1970, the first "readings" dedicated to the study and realization of the scientific heritage of F. A. Tsander were held in Riga, and adopted a resolution to hold "Tsander readings" systematically. The second "readings" were held in May of 1972 in Leningrad.

The name of Tsander has been given to a crater on the far side of the moon.

The Works of F. A. Tsander on Rocket Engines

F. A. Tsander, a great scientist in the area of the development of a broad range of problems on the theory of space flight, dedicated a significant portion of his scientific and technical activity to theoretical studies of the possibility of constructing highly efficient reaction flight vehicles, as well as theoretical and practical work on the mastery of liquid-fueled rocket engines during the initial period of their development in the USSR.

Many of the theoretical and experimental works of F. A. Tsander are dedicated to the finding of means for achievement of his basic idea, that the combustion of the metal parts of the rocket along with the liquid fuel after the parts were no longer needed could increase the exhaust velocity of the combustion products and also increase the ratio of the mass of fuel burned during the process of a flight to the final mass of the rocket.

This idea attracted F. A. Tsander as early as the 1920's, but was most completely presented by him in his work "The Problem of Flight Using Reaction Apparatus." In this work he presents a description of two flight vehicles: an airplane wit. a rocket engine, the wings of the airplane an. some other parts being drawn into the vehicle and melted to be used as fuel, and rockets surrounded by a set of containers filled wi*h fuel components, with the containers drawn into the central rocket after their fuel content was exhausted, then melted and used as fuel. /59

F. A. Tsander believed that only the designs which he suggested could achieve interplanetary speeds.

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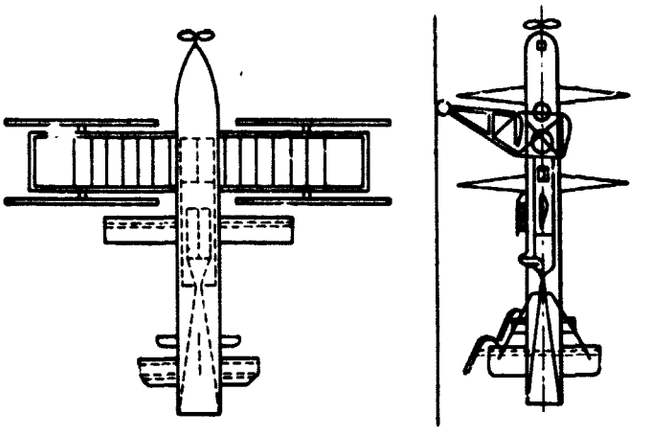
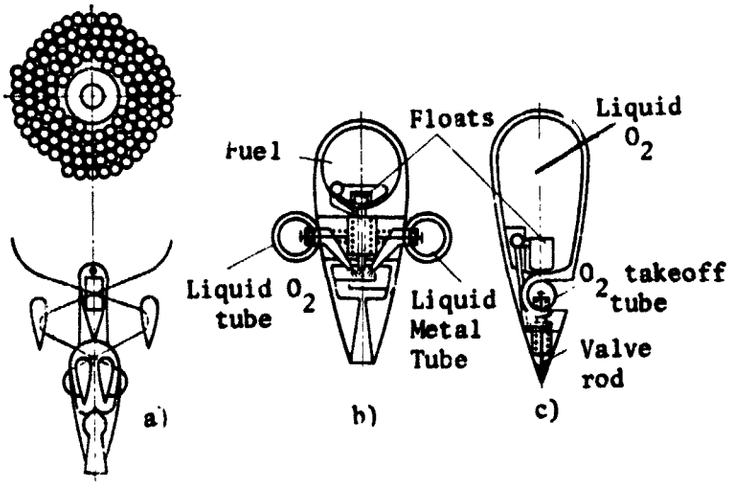


F. A. Tsander's Plan for the Interplanetary Spacecraft



Plan of Central Rocket Surrounded by Side Rockets and Fuel Tanks After F. A. Tsander

His total confidence in the correctness of the scientific and technical direction he had selected also determined the nature of his theoretical and practical developments. He turned his attention to theoretical study of possible means of increasing the sepcific impulse of his engine and the efficiency of its individual unit; theoretical study and experimental development of possible application of metals as additives to fuel; and theoretical study and experimental development of LRE.

In the early 30's, the level of technology and available structural materials did not allow a rocket with a high ratio of launch weight to final weight to be constructed (for example, in the first Soviet rocket with LRE, the GIRD-X, this ratio was approximately 1.4), so that the idea of F. A. Tsander was promising, but was found to be practically impossible.

In the best modern rockets, thanks to the use of the latest structural materials, optimal design of all rocket units and operation in the most suitable modes, very high ratios of launch weight to final weight have been achieved.

Investigation of Fuels

F. A. Tsander was a proponent of the use of fuels with low-boiling oxidizers. He based this opinion on the fact that this type of fuel has exceptionally great capabilities as concerns further increases in specific impulse. As an oxidizer, he believed it desirable to use liquid oxygen, with liquid hydrogen, gasoline or alcohol as the fuel. Gasoline, in particular, drew Tsander's attention not only by its high heat content, but also the possibility of its use in the aviation and rocket engines which he planned for interplanetary flight vehicles.

As we have stated, F. A. Tsander performed investigations on the possibility and expediency of using metals as additives to liquid fuel. As we know, when some metals burn, more heat is liberated than when liquid fuels are burned, even such liquids as gasoline; therefore, the addition of metal to a liquid fuel under certain conditions might cause an increase in the specific impulse. /60

For example, the heating ability of combustion products in oxygen, per kg of fuel, according to F. A. Tsander, are as follows: for gasoline -- 2350 kcal, for aluminum -- 3730 kcal, for lithium as high as 4710 kcal.

However, at the temperatures characteristic for LRE, solid oxide particles are generally formed. It is therefore impossible to calculate the exhaust velocity, thrust and specific impulse

by the formulas designed on the assumption of gas flow alone. F. A. Tsander studied the conditions of motion of products consisting of a mixture of gases and solid oxides. For example, in his article, "The Use of Metal Fuels in Rocket Engines,"[1] he presents an approximate determination of the reaction force produced by an engine expelling particles from its nozzle at two significantly different velocities. "It is possible," F. A. Tsander wrote, "to burn metal with liquid fuels in proportions such that no decrease in thrust is observed."[2]

In order to check his calculations and the practical possibility of utilizing the burning of metal in the chambers of reaction engines, F. A. Tsander first performed a number of simple laboratory experiments on the ignition and combustion of metals. Then, the combustion of metals was studied using the OR-1. Later, the program of experiments was expanded.

F. A. Tsander suggested that the metal fuel be made of those parts and units which had performed their functions and were no longer needed for flight or landing of the airplane-rocket or central rocket with many side rockets and liquid fuel and oxygen tanks which he designed.

For this reason, F. A. Tsander attempted to determine the possibility of processing individual structural elements into powdered or melted metal (magnesium, aluminum) and developed plans for engines allowing this idea to be realized. F. A. Tsander came to the conclusion that it was expedient to use /61
lithium as not only an additive to the fuel, but also as the structural material of a spacecraft.

In his article, "Problems of the Design of a Rocket Using Metal Fuel," published in 1937, the requirements are set forth for metals of which the structural elements later to be burned in the combustion chamber were to be made. They are as follows: the metal should be sufficiently strong at normal temperatures, the light and heat of melting should not be too great, the heat generating capacity should be as great as possible, the melting point -- low. His work presents a method for determination and selection of the optimal dependence between the mass of a metal on the one hand, and of the liquid oxidizer and fuel on the other; between the masses of all structures and of the metal burned, between the solid and gaseous combustion products.

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[1] Raketnaya Tekhnika, 1936, No. 1.

[2] Tsander, F. A., Problema Poleta pri Promoshchi Reaktivnykh [The Problem of Flight Using Reaction Apparatus -- Collection of Works], Moscow, Oborongiz Press, 1961, p. 241.

In his work "The Problem of Flight Using Reaction Apparatus," the use of boron or liquid boron hydride as an additive to the fuel, suggested earlier by Yu. V. Kondratyuk, was studied. "However, boron will probably be used only as a powder for insulation (amorphous boron) or in the form of rods subject to compression (crystalline boron). Liquid boron hydride could also be taken if kept very cold."[1] When boron burns in oxygen, the minimum quantity of solid product is produced with very high heat liberation, which Tsander calculated at 3900 kcal/kg.

This work also suggests that solid nonmetallic materials such as celluloid, etc. be used as additives to liquid fuel. "Experiments could also be conducted to find pressed masses, used in almost all areas of chemical technology and possible for our purposes as well." And further... "We can imagine masses containing naphthalene or other fuels in mixture with materials which, when heated, would melt and then be fed from the melting vessel into the motor pumps of the rocket as liquid fuel."[2]

Study of Processes Within the Chamber and Cooling Conditions /62

F. A. Tsander developed methods for thermal and thermodynamic calculation of a reaction engine, presented in two articles under the title "Thermal Calculation of a Liquid-Fueled Rocket Engine," first published in 1936-1937.

In these articles, the author presented examples of calculations for a fuel consisting of air enriched in oxygen and gasoline. There also he analyzed the influence of the adiabatic index, gas constant, gas temperature and degree of expansion on the ideal exhaust velocity of gases from the nozzle; he presented a method for determination of the area of the critical and exit-plane cross sections of the nozzle; he studied the flow of actual gases considering loses and considering the influence of gas friction on the wall on the characteristics of the nozzle.

F. A. Tsander determined the combustion temperature considering dissociation of gases and constructed graphs characterizing the thermal parameters of an engine as a function of the oxygen content in the oxidizer.

In these articles, F. A. Tsander performed his calculations not only analytically, but also using entropy diagrams.

[1] Tsander, F. A., Problema Poleta pri Promoshchi Reaktivnykh [The Problem of Flight Using Reaction Apparatus -- Collection of Works], Moscow, Oborongiz Press, 1961, p. 119.

[2] Ibid., p. 117.

A number of the works of F. A. Tsander have been dedicated to determination of the heating and cooling of the walls of a rocket engine combustion chamber. These works analyze the peculiarities of heat transfer from the gases to the walls of LRE. The most detailed thermal calculation of the cooling system for a rocket engine is presented in the article "Thermal Calculation of a Rocket Engine Designed for Liquid Fuel."[1] In it, the heat transfer coefficient is calculated on the basis of the formula of Nusselt, after which formulas for determination of the external, internal and average temperature of the engine chamber wall are given, methods are studied for determination of the physical parameters of cooling media and the required flow rates.

Calculation of the cooling system helped F. A. Tsander to determine the limiting possible pressure in the chamber for each specific fuel composition. Using the results of calculations, he determined the thermal efficiency, thrust of the engine, exhaust velocity and selected the volume of the combustion chamber. Thus we see that the planning and construction of the OR-1 and OR-2 engines were preceded by calculation. /63

The scientist set himself the problem of transfering rocket technology from the area of theory to the area of engineering practice. "I am primarily a mathematician," Fridrikh Arturovich said of himself. However, analyzing the results of his activity, we can bravely state that F. A. Tsander was a great scientist, inventor, engineer, designer and experimenter. He created a number of experimental installations, a flame stand, created and experimentally developed the OR-1 reaction engine, developed the OR-2 rocket engine and the initial version of the GIRD-X rocket with the type 10 rocket engine.

Increasing Specific Impulse and Efficiency

F. A. Tsander studied various means for increasing specific impulse. Giving this problem prime importance, he based his studies on the use of a fuel with high specific heat content, consisting of liquid oxygen and gasoline, and considered the use of oxygen most promising. In addition to the use of metal as an additive to fuel in order to increase its heat-producing capability, he also suggested that specific impulse be increased by acting directly on the gases leaving the chamber of the rocket engine by installation of restricting fittings at the end of the expanding nozzle, the so-called reverse cone.

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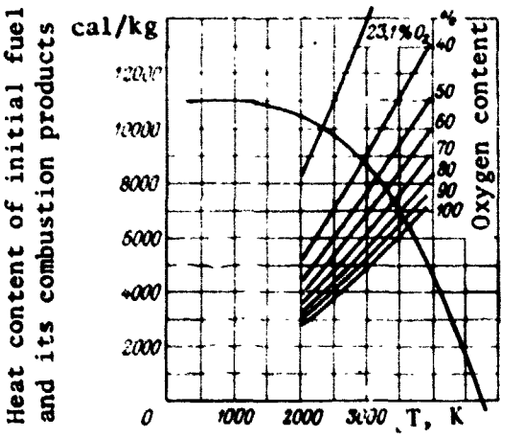
[1] Raketnaya Tekhnika, No. 1, 1936.

As heat is transferred from the supersonic stream to the constricting fitting, the gas velocity should increase.

The increment in work of the cycle is obtained by the additional adiabatic expansion (line CE) and subsequent isothermal compression (line EF). F. A. Tsander called this cycle the improved working cycle. The pressure at the outlet of the nozzle p_a remains at the design level, and optimal thrust is achieved; the temperature of the gases leaving the nozzle T_a is decreased, consequently increasing the heat drop generated in the combustion chamber. However, F. A. Tsander did not consider the presence of compression jumps in the supersonic stream and did not study the possibility of producing effective cooling of the entire mass of exhaust gases.

At the present time, thermal efficiency is increased by increasing the degree of expansion of the gas by increasing the pressure in the chamber with the optimal gas pressure at the exit plane of the nozzle. /64



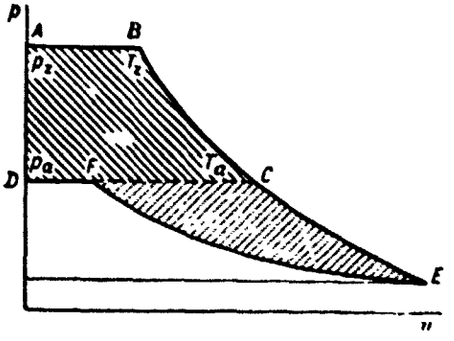
Results of Thermodynamic Calculations of the OR-1 Reaction Engine After F. A. Tsander

In 1930, F. A. Tsander developed an approximate method for calculation of a reaction engine. He gave particular attention to the calculation of thermodynamic processes in the combustion chamber, allowing him to determine the basic parameters of the LRE with the necessary accuracy as they were planned. During these years, the approximate method of design of a rocket engine was developed and successfully used by V. P. Glushko at GDL. Later, methods of thermodynamic calculation considering dissociation were improved in the USSR by V. P. Glushko, A. P. Vanichev, A. I. Polyarnyy and other scientists.

The OR-1 Reaction Engine

The first experimental reaction engine (OR-1) used compressed air and gasoline. The planning and construction of the OR-1 were preceded by laboratory experiments and careful calculations performed by F. A. Tsander. In 1917, he performed

experiments on the burning of metal; beginning in 1922, he selected and systematized the calculation dependences, without which it was impossible to create the method of calculation of LRE, developed plans and drawings for an experimental reaction engine, and on 30 November 1928, F. A. Tsander read a report /65
at Moscow University entitled "Preliminary Work on the Construction of a Rocket Apparatus," in which he presented the results of preliminary calculations and a plan which served as the basis for development of the OR-1.



Indicator Diagram of Theoretically Improved Engine of F. A. Tsander

In October of 1929, F. A. Tsander began detailed design calculation of the OR-1 engine.

The initial calculation data were: gasoline consumption 350-400 g/hr, theoretical air consumption per kg of gasoline -- 14.2 kg. Thus, the fuel consumption was approximately 1.67 g/sec. Thermodynamic calculations determined the composition of the combustion products, gas temperature in the combustion chamber, approximately 2440 K, thermal efficiency, on the order of 0.105-0.125, exhaust velocity, about 840 m/sec, and design thrust -- 0.145 kg.

F. A. Tsander began assembling his engine immediately after completion of the calculations and manufacture of the parts.[1]

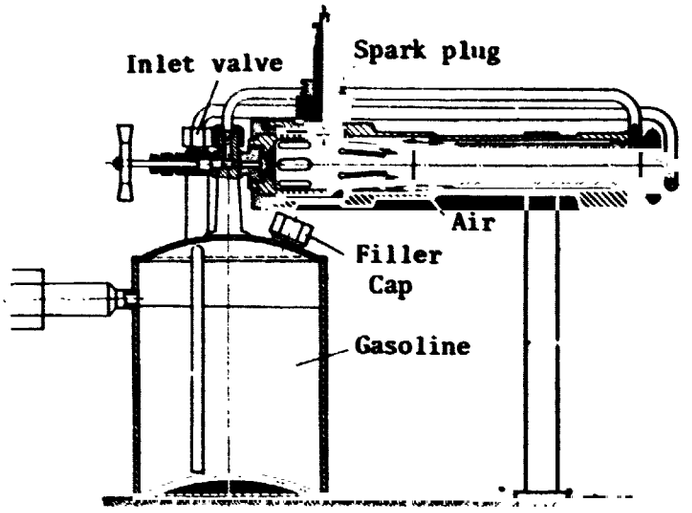
On 30 September 1929, he wrote: "Due to the funding problem, I suddenly got the idea to redesign the torch for the first reaction engine... I redesigned the fitting and surrounded it with a sleeve, into which air was blown under pressure. Inside the sleeve was a special tube forming the space for combustion. At the end of this tube was an interchangeable conical fitting to produce exhaust velocities greater than the speed of sound.

"The copper tube for liquid gasoline was replaced with a longer one, which was wound around the conical fitting to preheat the gasoline. Furthermore, the tank was equipped with a manometer to measure the gasoline feed pressure and a nipple to let /66

[1]The descriptions of the OR-1 presented by a number of authors include many individual errors; we therefore considered it expedient to present the description of the OR-1 given by Tsander himself.

out air. A thermometer was attached to the tank to measure the tank cover temperature. A special valve was fitted to regulate the consumption of fuel.

"The compressed air for combustion and cooling of the combustion chamber was fed into the cooling line through a nipple attached to the sleeve in front of the nozzle. The mixture was ignited by a spark plug soldered into the head."[1]



The First Reaction Engine - the OR-1

The first tests of the OR-1 were conducted by F. A. Tsander in the laboratory for air aviation engines of the screw-motor section of TsAGI in 1930. The engine was suspended so that the gases exiting from the nozzle were directed toward a small metal disc connected to a balance. The indications of the balance were used to determine the pressure of the gases on the disc.

In 1931, the OR-1 engine was finally developed and beginning in 1932 it was used to study the influence of the addition of metals to the liquid fuel on thrust. The low accuracy of the measurements characteristic of the time and the insufficient thrust developed by the OR-1 did not allow any influence of these additives on the operating mode of the engine to be measured, but calculations still indicated the expediency of the use of metal additives to the fuel. Therefore, studies were continued in later years. /67

The OR-2 Rocket Engine

The OR-2 engine was developed by F. A. Tsander. The planning of the engine was begun in September of 1931, but preliminary calculation of the units and of the engine as a whole had been conducted by Tsander even earlier. The engine was designed for

[1]Tsander, F. A., Problema Poleta pri Promoshchi Reaktivnykh [The Problem of Flight Using Reaction Apparatus -- Collection of Works], Moscow, Oborongiz Press, 1961, p. 47.

installation on a piloted vehicle -- the RP-1 "flying wing" glider designed by V. I. Cheranovskiy. This glider was manufactured by Osoaviakhim activists.

Thus, the OR-2 is the first domestic LRE designed for a piloted vehicle. Liquid oxygen and gasoline were selected as the fuel. The operating time of the engine was designed to be 30 sec, with a thrust of 50 kg and a chamber pressure of 6 to 8 atm. However, the OR-2 was never installed on the RP-1 glider, since the engine was never successfully developed. Later, not at GIRD but rather at RNII, a modification of the engine (02) was developed, differing from the OR-2 in design and fuel used.

The combustion chamber of the OR-2 had an elongated cylindrical shape, the nozzle was conical and supersonic. The mixing head carried sprayers and an inlet valve for the fuel. This same valve allowed thrust to be varied by gradually changing the fuel consumption. Ignition was by an electric spark plug. The cylindrical portion of the chamber of the engine was cooled externally by the liquid oxygen, which entered the chamber in gaseous form, and the nozzle was cooled with water.

The extractive feed system included pear-shaped fuel tanks, which were to be suspended in the internal sections of the glider. The fuel components were fed to the chamber under pressure created by gaseous nitrogen. This was achieved by the use of a "nitrogen compensator" -- a separate tank containing liquid nitrogen. The water cooling system for the nozzle included two liquid oxygen evaporators, the nitrogen compensator heat exchanger, a water tank and pump. The water, heated in the nozzle cooling cavity, passed through the pump and tank into the nitrogen compensator and evaporators. Heat exchange between the water and the liquid nitrogen caused the latter to evaporate. Additional cooling of the water occurred in the oxygen evaporators. The oxygen gas was used to pressurize the oxygen tanks. The cold water was returned to the nozzle cooling cavity. All parts of the OR-2 were placed in the glider. Assembly of the OR-2 engine was completed in December of 1932. /69

By early March 1933, the engine was installed on a test stand at the Nakhabinsk range and prepared for testing. Since Fridrikh Arturovich was then in Kislovodsk for treatment, the flame tests were performed by his working colleagues. /70

The first test of the OR-2 was held on 18 March 1933. The feed pressure was first held rather low -- from 3 to 4 atm. The fuel in the chamber ignited, but the combustion was unstable and rough and in a few seconds the engine had to be shut off. During the second test on 21 March 1933, one oxygen evaporator operated. During the seventh second, the motor burst in the region of the head. The third test was conducted on 26 March. The feed

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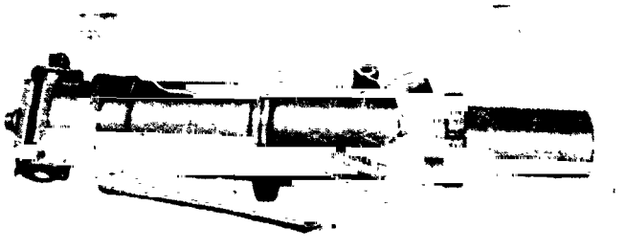

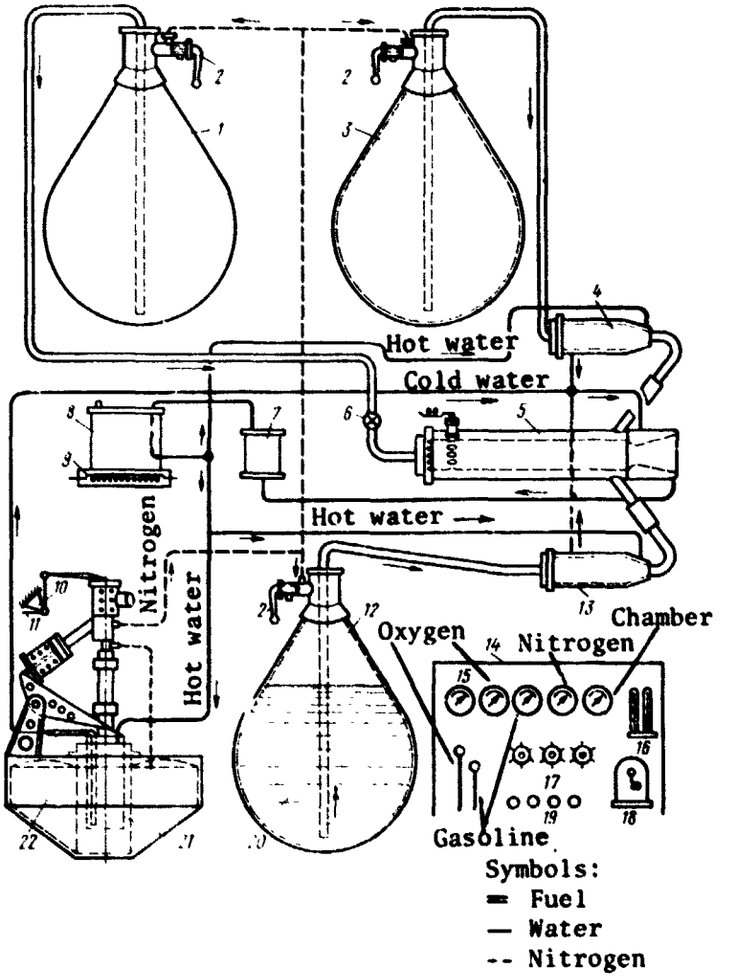

Diagram of the OR-2 Engine and External View of Its Chambers: 1, Gasoline Tank; 2, Safety Valve; 3, 20, Oxygen Tanks; 4, Evaporator; 5, Combustion Chamber; 6, Valve; 7, Pump; 8, Water Tank; 9, Additional Heating; 10, Roller; 11, Line; 12, Nitrogen Under Pressure; 13, Evaporator; 14, Control Panel; 15, Manometers; 16, Thermometers; 17, Valves; 18, Magnito; 19, Valves; 21, Cylinder of Hot Water; 22, Nitrogen Compensator

system was operated with two evaporators, but the combustion of the fuel in the chamber was rough, and in a few seconds the chamber burst on a welded seam. The cooling jacket burned through. During the fourth test, on 28 April 1933, the pressure in the chamber changed suddenly, but at times briefly stabilized and held almost constant at 8 atm; the feed system operated with two evaporators. In danger of damage due to the great dynamic loads developed, the engine was shut down in the 35th second.

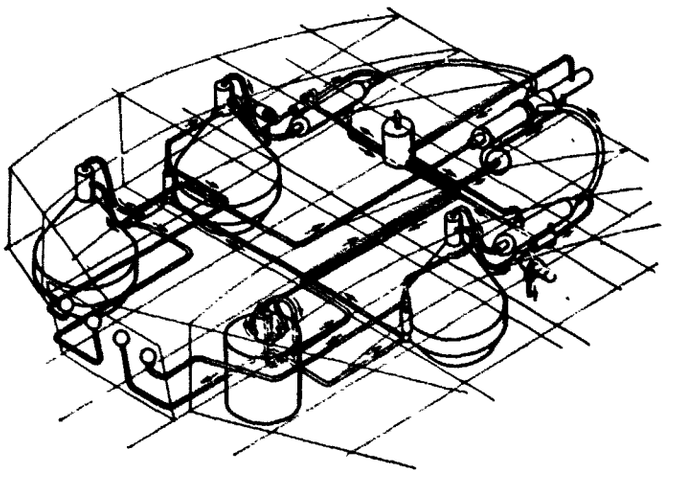

Diagram of Placement of OR-2 Engine Components on the RP-4 Glider

During the first tests of the OR-2, the members of the team held to the working style of F. A. Tsander and followed his instructions to test the entire motor at once, i.e., the combustion chambers together with the fuel feed system and supplementary apparatus. This method of testing is more complex than stage-by-stage development of units but, as Fridrikh Arturovich believed, it allowed more complete consideration and clearer determination of the interrelationship of all processes occurring in the engine.

It is hard to decide what plan of further testing F. A. Tsander would have suggested after analysis of the results of the first flame tests. We know that he did not deny the possibility of using oxygen-alcohol fuel; therefore, after processing of the experimental data, gasoline was replaced by ethyl alcohol in further experiments.

The combustion chamber was simplified and equipped with a refractory heat insulating lining consisting of aluminum oxide and magnesium oxide; an extractive fuel component feed system was installed, consisting of the fuel tanks and a gas accumulator -- a high pressure cylinder. A valve an reducer were installed between the cylinder and tanks in order to reduce the pressure. This new version of the engine was called the 02. Subsequently, only the combustion chamber, rather than the entire engine with all of its units was developed. The description of the 02 engine is presented below. /71

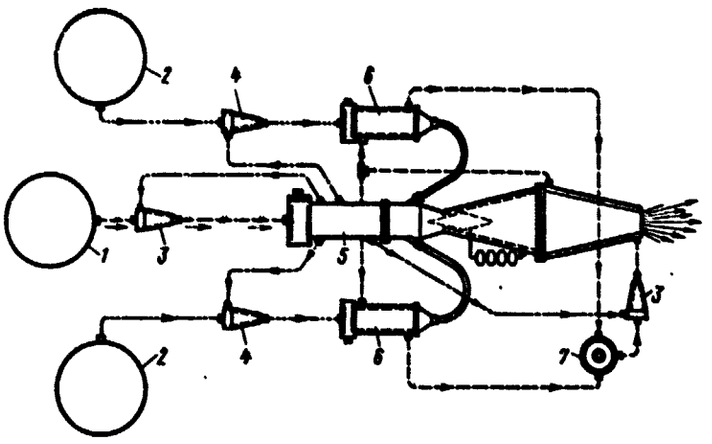

Diagram of Second Version of 5T Rocket Engine After F. A. Tsander: 1, Liquid Fuel; 2, Oxidizer; 3, Injector; 4, Heater or Injector; 5, Combustion Chamber; 6, Oxidizer Evaporator; 7, Compensator

Plans of Rocket Engines

In addition to the OR-2 engine with the extractive feed system, F. A. Tsander developed several other designs with injector fuel component feed. K. E. Tsiolkovskiy believed that injectors could use a portion of the energy liberated in the combustion chamber to feed liquid fuel components by means of a stream of gas. F. A. Tsander did not produce such systems.

F. A. Tsander made up a general engine plan with a turbine-pump fuel-feed system, and suggested that a gas turbine be used to drive the pump, the working fluid for which would be the combustion products of the fuel, drawn away from the main combustion chamber. At the present time, in order to produce turbine gas of relatively low temperature, the turbines are supplied not by the combustion chamber, but rather by gas generators.

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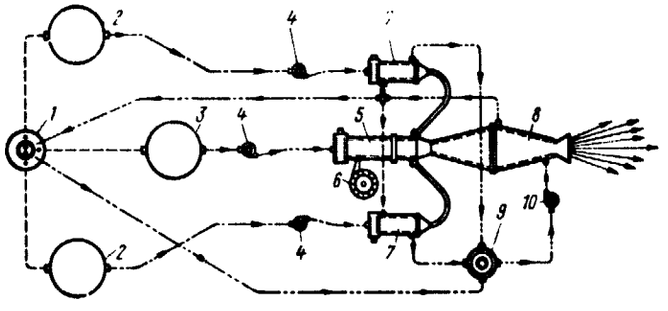
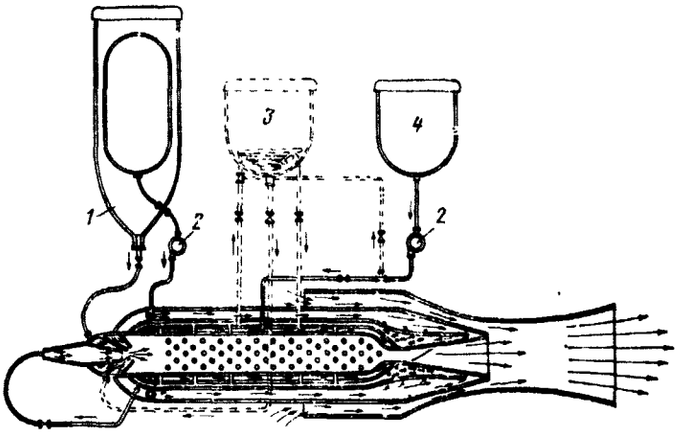


Diagram of Third Version of 5T Rocket Engine After F. A. Tsander: 1, Into Evaporator; 2, O_2 or N_2O_4 or Ozone, 3, Alcohol or Other Fuel; 4, Pumps; 5, Combustion Chamber; 6, Gas Turbine; 7, Evaporator; 8, Double Cone; 9, Water Compensation Tank; 10, Water Pump

One interesting design developed by F. A. Tsander is an engine plan in which, in addition to the usual liquid fuel, powdered and liquid metal fuel were to be used. The powdered metal was to be fed into the combustion chamber by an injector. The liquid metal was to be produced by melting metal structural elements of the rocket no longer necessary in flight.



Di gram of Engine 10 for Initial Version of Liquid Fuel Rocket After F. A. Tsander: 1, Powdered Metal Fuel; 2, Pump; 3, Solid Fuel; 4, Liquid Fuel

The studies performed in the 30's and 40's with injectors showed that, in spite of some promising theoretical data, they operate only at very low efficiencies.

Attempts to develop an acceptable engine design using metal as an additive to the primary fuel were unsuccessful. Attempts to construct units for melting or pulverizing of metal were also unsuccessful. Therefore, two very interesting ideas from the plans of F. A. Tsander, the use of injectors and of metal fuel, have not as yet been practically realized.

Fridrikh Arturovich Tsander was one of the pioneers of rocket technology, combining the talent of a great theoretical scientist and that of a gifted experimenter and engineer. He developed the principles of the theory and design of LRE and performed detailed calculations of his first experimental specimens. The theoretical and experimental developments of Fridrikh Arturovich aided further development of research on LRE and rockets, while the propagandistic activity of Tsander and other enthusiasts led not only to the creation of GIRD in Moscow, but also in many other cities of the country. Thanks to the practical activity of F. A. Tsander at GIRD, the first Soviet rocket with LRE was created and the OR-2 engine was developed.

Move forward bravely, great and small laborers of the world, and know that not a line of your work will be lost, but will bear for you great fruit.

K. E. Tsiolkovskiy

Chapter 2. The First Rocket Scientific Research and Experimental Design Organizations in the USSR /74

The works of the early scientists of our country, their students and followers formed a basis for the development of scientific research and experimental design work on the creation of rocket engines and rockets in the early 1920's.

The reason for this development was not only the successful results of the studies of our scientists, but also, to a significant extent, the demands of various branches of science and technology, particularly aviation and artillery

Thus, in the 20's the time had come for the transition to experimental work, for the creation of creative teams and the expansion of the range of scientific research work. Rocket technology had to be brought from the area of theory to the area of engineering practice, had to be given statewide significance. "But we must undertake experiments. We must consider nothing in our theoretical works to be absolutely true,"[1] said K. E. Tsiolkovskiy.

The development of the national economy, the rapid growth of science and technology in the USSR, the successful fulfillment of the first five-year plan allowed scientific research organizations to be set up on the country for the development of rockets and liquid-fueled rocket engines.

During these same years in the Soviet Union, many public /75 organizations were developed which were of great significance in the popularization and development of rocket and space technology. Some individual scientists made great contributions to the development and popularization of the science of rockets and engines.

The leading organizations in the USSR were the Gas Dynamics Laboratory (GDL) under military auspices, which began its

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[1]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 274.

activity in the spring of 1921, the Group for the Study of Rocket Motion (GIRD), a publically supported group begun in the fall of 1931, and the Reaction Scientific Research Institute (RNII), developed on the basis of GDL and GIRD late in 1933. The rocket organizations expanded, changed their purposes, new large government enterprises were developed, solving complex problems of the mastery of space.

Now, probably, it would be simply impossible to list all of the large and small problems, the entire range of problems studied by the subduers of space. There is no science or technology which has not been utilized to some extent in the study of space; it is difficult to name a science whose development has not been influenced by the results of the study of space. The performance of such a grandiose program of difficult investigation, leading to the accumulation of a new wealth of knowledge by mankind, requires the harmonious development of all areas of science and technology, leading to an avalanche of inventions and discoveries.

However, things were different during the first years of development of rocket technology. It was impossible then to begin immediately to solve problems of cosmic scale. Even Sergey Pavlovich Korolev believed that dreams of flights to the moon and of new speed records by rocket airplanes not yet in existence were useless until scientists could create at least small liquid-fueled rockets. For this reason, every researcher, every worker in the area of rocket technology had to hold the reaction engine at the center of his attention. If a reliable engine could be built, Sergey Pavlovich believed, all other problems arising in the process of work with the flight vehicles could be successfully solved. "Our success," S. P. Korolev wrote, "requires first of all a reliable, high quality motor."[1] /76

It is therefore quite clear that the main task of GDL, GIRD and RNII was the creation of LRE corresponding fully to the requirements placed upon them.

2.1. The Initial Period of Development of GDL -- the N. I. Tikhomirov Laboratory

Nikolay Ivanovich Tikhomirov and his immediate colleagues, Vladimir Andreyevich Artem'yev, Georgiyey Erikhovich Langemak, Boris Sergeyevich Petropavlovskiy and many others made a great contribution to the problem of creation of military rockets with powder rocket engines.

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[1] Korolev, S. P., Raketnyy Polet v Stratosfere [Rocket Flight in the Stratosphere], ONTI Press, Moscow, 1934.

Their work on the creation of rockets burning smokeless powder resulted in many models of rockets of various sizes and purposes which were used by the Soviet Army, including the new combat weapons developed in 1941 and widely used in the Second World War, the guard's mortars.

Chemical engineer N. I. Tikhomirov (1860-1930) performed experimental work as early as 1894 to determine the forces of reaction of powder gases in order to utilize the reactive force to power military devices. In 1912, Tikhomirov presented a schematic description of a shell to the Naval Ministry. In 1912-1917, this plan was further developed and successfully passed many tests, although conditions were provided for its production only after the revolution. In May of 1919, Tikhomirov sent to the Administrator of the Council of People's Commissars V. D. Bonch-Bruyevich a request to call the attention of Comrade Lenin to the need to produce his invention in order to defend the young workers and peasants republic. N. I. Tikhomirov attached a description of his invention, the Certificate of Invention which he was awarded in 1915 and the positive report of the Chairman of the Department of Inventions of the Moscow Military and Industrial Committee (VPK), Professor N. Ye. Zhukovskiy, awarded in 1916, to his letter. After objective study of the plan in the Committee for Inventions and the Artillery Committee, /77
the Commander in Chief of all armed forces of the republic, S. S. Kamenev, and the Revolutionary Military Council of the Republic ordered rapid development of work on the invention of N. I. Tikhomirov in a number of documents. These documents note the value of the invention of N. I. Tikhomirov and point out that it was considered to have significance for the state. In March of 1921, N. I. Tikhomirov was given work space in Moscow on Tikhvinskaya Street (two story building No. 3) to set up a laboratory and shop, and was also awarded the necessary funds. According to the documents on financing and material support, the beginning of the organization of the laboratory can be dated as 1 March 1921.[1]

Nikolay Ivanovich Tikhomirov

In May of 1921, the Artillery Committee sent V. A. Artem'yev, the "rocket affairs expert," as he was called in the Artillery Committee, to help N. I. Tikhomirov.

Vladimir Andreyevich Artem'yev (1885-1962) began to work on the construction

[1]For more detail on the organization of the GDL, see Vestnik Akademii Nauk SSSR, 1972, No. 2, pp. 100-108.

of military rockets in 1913. At that time, he was serving at the Brest-Litovskaya fortress and, as head of a laboratory, was studying the improvement of the three-inch rocket flares produced by the Nikolayevskiy Plant and used by the armed forces. /78

In 1921, shops, a pyrotechnical laboratory and a chemical laboratory were set up. This complex was called the "N. I. Tikhomirov Laboratory" and was subordinate to the Military Department. However, the work on the creation of military rockets moved forward very slowly; difficulties arose primarily due to the lack of high-energy, slow-burning powders. It became obvious that development of self-powered mines would require significant funds and time. Therefore, in April of 1923 the inventors were ordered to perform experimental tests of the applicability of reaction power for existing mines in order to increase their range.

Between 22 March and 3 April 1924, 21 launches of these rockets were conducted at the main artillery range in Leningrad under the direction of V. A. Artem'yev, showing a ten-times increase in range of the mortar shells used. These experimental tests confirmed the promise of the new type of shell and the need to perform further work in this direction.

The experience of preceding investigations had indicated the inapplicability of available powders for the manufacture of rockets, since they did not burn evenly, or were not sufficiently effective. Smokeless pyroxylin powder, widely used in artillery, did not yield positive results.

Smokeless powder (pyroxylin cartridge powder) was first suggested for rockets in 1915 by I. P. Grave, but the rockets being developed required slow-burning powder charges with great top thickness. The preparation of such charges using known formulas for pyroxylin powder based on volatile solvents encountered unsurmountable difficulties. The charges were warped and cracked during drying, resulting in variations in burning time and speed. Consistent results also could not be achieved in the percent content of solvent remaining in the charges after drying. During storage of the charges, the solvent evaporated, also causing variation in the parameters of combustion of the powder charges.

In order to avoid these shortcomings, N. I. Tikhomirov decided to try smokeless powder with a nonvolatile solvent. The development of this smokeless powder was undertaken in 1922 under the leadership of N. I. Tikhomirov in Leningrad with the participation of O. G. Fillipov and S. A. Serikov. This work was of great scientific and practical significance for the development of rockets and space technology. The first specimens of thick-top powder drains of the new formula -- trotyl-pyroxylin powder /79

(using trotyl as the nonvolatile solvent) -- were produced in 1924. This powder, called PTP, was then manufactured in the powder shops of the Leningrad Steamship Port. These shops were assigned to N. I. Tikhomirov, and became a part of the laboratory. Powder testing was conducted at the Scientific Research Artillery Range near Leningrad. Powder studies were continued at the Military-Technical Academy imeni F. E. Dzerzhinskiy in Leningrad.

The basic model used in testing and experimental development of charges was a grain with an external diameter of 24 mm and an internal channel 6 mm in diameter. Later, the grain diameter was increased to 100 mm.

The creation of a stable high-energy smokeless grain powder with great top thickness was a great achievement, providing a qualitative jump in the development of solid-fuel rocket design.

All of the most important work of the laboratory, related to the development and manufacture of a smokeless powder, test stand operation and experimental firing, was conducted at Leningrad. As a result, in 1925 the laboratory was transferred to Leningrad completely.

After careful development and testing of grains and launching devices, on 3 March 1928 the first firing of rockets with charges of smokeless trotyl pyroxylin powder was conducted at the main artillery range.

In his memoirs, V. A. Artem'yev wrote that no data have been found indicating that foreign armies successfully tested rockets using smokeless powder earlier than our own.

The creation of a smokeless powder rocket laid the foundation for the design of the "Katyusha" military rockets.

2.2. The Gas Dynamics Laboratory /80

Following the successful launch of smokeless powder rockets in 1928, the N. I. Tikhomirov Laboratory was expanded and renamed the Gas Dynamics Laboratory (GDL), subordinate to the Military Scientific Research Committee of the Revolutionary Military Council, USSR. The first task of the GDL was the development of solid-fueled rockets utilizing high-quality smokeless powder charges. Soon, GDL also undertook the creation of powder takeoff assist and landing brake rockets for airplanes. Based on the successful results of experimental work by N. I. Tikhomirov and V. A. Artem'yev involving the creation of rockets, the Main Artillery Administration of the Red Army decided to send specialists to the GDL and to expand its production and laboratory base.

The primary experimental research base of GDL was stationed in 1928 at the Scientific Research Artillery Range (NIAP) near Leningrad, the Design Bureau -- in a building at the Artillery Scientific Research Institute, then at the Admiralty, the Administration -- in Lengrad at No. 19 Khalturin Street, the powder shop -- at the steamship port, the aircraft testing base -- at the military airfield, the mechanical shops -- at Petropavlovsk fortress and elsewhere.

The Gas Dynamics Laboratory was greatly aided by the Chairman of VSNKh, later People's Commissariat for Heavy Industry, G. K. Ordzhonikidze and, particularly, by Marshall of the Soviet Union M. N. Tukhachevskiy, the immediate superior of the GDL.

Boris Sergeyevich Petropavlovskiy

In 1930, at the age of 70, N. I. Tikhomirov died. On the 50th Anniversary of the foundation of the GDL, a monument to its creator and leader, patriot and scientist N. I. Tikhomirov, was erected at the GDL. The name of N. I. Tikhomirov is permanently inscribed in the history of rocket technology in the USSR and has been given to one of the craters on the far side of the moon.

In 1930, the GDL was taken over by a talented military artillery engineer, Boris Sergeyevich Petropavlovksiy. From 1930 to 1933, powder rocket bombs of various sizes were developed at GDL, including 60, 65, 70, 82 and 132 caliber. In mid-1931, the rockets produced at GDL were used as a basis for plans for aircraft takeoff assist devices, and practical firing tests of the RS-82 air-to-ground rocket were conducted from an I-4 airplane in 1932. In the summer of 1932, official firing of /81
the RS-82 from the I-4 aircraft was conducted, using an airplane armed with 6 rocket launchers.

Together with the improvement of air-to-ground rockets, extensive studies were conducted on the use of ground-launched rockets fired by special lightweight launching devices.

During the Second World War, a very significant weapon was the barrelless mutliple-charge mortar -- the BM-13-SN, BM8-48, BM31-13 launchers and their modifications designed to fire rockets. During the war, the people called this weapon "Katyusha."

The development of the Katyusha launcher can be divided into three main stages. During the first stage (1921-1929), the smoke-

less powder was developed, the principles of design of solid-fueled rockets were determined and flight testing was begun; in the second stage (1930-1933), rockets were produced, passed official testing and during the third stage (1933-1941), the Katyusha rocket launcher was developed.

Experimental work with solid-fueled aircraft takeoff boosters and landing braking devices began in 1927 using a powder catapult, then later with the U-1 training aircraft. Beginning in late 1931, work on a solid-fueled takeoff assister was conducted with the TB-1 aircraft. On 14 October 1933, the TB-1 aircraft, equipped with a rocket-assisted takeoff device, successfully passed state testing; the use of RATO reduce takeoff run length by 77% with a flying weight of 8 t. RATO devices were developed by B. S. Petropavlovskiy, G. E. Langermak and other. V. N. Dudakov, pilot S. I. Mukhin and mechanic A. I. Gritskevich assisted significantly in the development of takeoff techniques. /82

In 1933, work was begun on a RATO device for the TB-3 aircraft, flying weight 20 t. In 1934, the Red Army Air Force Command decided to conduct tests of reaction takeoff boosters on three TB-1 aircraft. One test aircraft undertook a special test trip from Leningrad to Moscow and back. On the whole, the tests confirmed the effectiveness of the use of such boosters. The advantages of aircraft takeoff with boosters became obvious to all.

In addition to the development of rockets and rocket engines based on solid fuels, beginning on 15 May 1929, GDL began to work on the first domestic rocket engines: electric engines (ERE) and liquid-fueled engines (LRE). In 1931, GDL was divided into seven sectors (called sections after 1932): 1 -- Powder Rockets (Chief G. E. Langemak); 2 -- Liquid-Fueled Rockets (Chief V. P. Glushko); 3 -- Aviation Applications of Rockets (Chief V. I. Dudakov); 4 -- Military Rockets (Chief N. A. Dorovlev); 5 -- Powder Production (Chief I. I. Kulagin); 6 -- Production Section (Chief Ye. S. Petrov); 7 -- Administrative and Financial Section. Between 1930 and 1933, the number of workers increased from 23 to approximately 200 persons.

The organizer and leader of the work of ERE and LRE, the designer of the world's first electrothermal rocket engine and the first domestic LRE, was Valentin Petrovich Glushko.

The development of the ERE and LRE involved the participation of V. I. Serov, A. L. Malyy, Ye. N. Kuz'min, I. I. Kulagin, Ye. S. Petrov, P. I. Minayev, B. A. Kutkin, V. P. Yukov, N. G. Chernyshev, V. A. Timofeyev, N. M. Mukhin, I. M. Pan'kin and others. The names of many of the scientists of GDL have been given to craters on the far side of the moon. /83

V. P. Glushko was born on 2 September 1908 in Odessa. He began to study problems of rocket flight in 1921. In 1923, he began corresponding with K. E. Tsiolkovskiy, who mentioned V. P. Glushko in the foreword to his books "Investigation of Space with Reaction Devices" (1926), "Space Rocket Trains" (1929) and other publications among those persons facilitating the popularization of the ideas of star flight by their publications.

From 1922 to 1924, V. P. Glushko worked at the Odessa astronomical observatory as an astronomical observer. The results which he produced were published in 1924-1925 in the Astronomical Bulletin and the Journal of "Mirovedeniye" Society. The young astronomer was selected as an Associate Member, then an Active Member of the Russian Society of Astronomy Enthusiasts (ROLM). Upon completion of his studies at the Department of Physics and Mathematics of Leningrad State University (1925-1929), V. P. Glushko began work at the Gas Dynamics Laboratory. His thesis, dedicated to the development of rocket engines, attracted interest and was approved by the experts of the Department of Military Inventions (N. I. Tikhomirov and M. V. Shuleykin). The materials of his thesis served as the first basis for the development of experimental ERE and LRE at the Gas Dynamics Laboratory. V. P. Glushko is the author of a number of scientific articles and fundamental works, including the books "Rockets, Their Design and Application" (together with G. E. Langemak, 1935), "Liquid Fuel for Reaction Engines" (1936), etc.

A leading scientist in the area of physical and technical problems of energetics, V. P. Glushko was selected in 1953 as a Corresponding Member of the Academy of Sciences USSR, in 1958 as an Academician. He has been twice named a Hero of Socialist Labor, is a Lenin and State Prize Laureate. Valentin Petrovich has been repeatedly elected as a deputy to the USSR Supreme Soviet. In 1972, the International Aviation Federation (FAI) awarded V. P. Glushko an international certificate as a great Soviet scientist in the area of development of rocket technology and investigation of the physical and technical problems of energetics. The FAI resolution is an international acknowledgement of the great contribution of our country to the study and investigation of space. /84

At the Gas Dynamics Laboratory, the possibility of practical creation of an electric rocket engine was proven in 1929-1930. However, it was not possible at that time to solve the entire range of problems related to the final development of ERE.

Therefore, the primary attention of the Gas Dynamics Laboratory was concentrated on the development of LRE and the investigation of processes of operation of these engines. In 1930, V. P. Glushko suggested and subsequently studied various fuel

components: nitric acid, solutions of nitrogen tetroxide in nitric acid, tetranitromethane, hydrogen peroxide, perchloric acid, beryllium, liquid fuels and powders with dispersed beryllium; in 1933, he suggested a mixture of liquid oxygen and liquid fluorine as oxidizer, and solutions of pentaborane in kerosene as fuel, as well as a fluorine-hydrogen fuel and many others.

In 1931, he suggested hypergolic fuel and chemical ignition.[1] The fuels used included gasoline, kerosene, toluene, benzene and others.

During these same years, experimental development of individual elements of liquid-fueled rocket engines was conducted. Ceramic insulation based on zirconium oxide and magnesium oxide was tested in the combustion chambers of experimental powder engines (1930). These combustion chambers were also used for ballast pendulum tests to determine the most favorable for the time exponential nozzle contour (1930). Measurement apparatus was created for test stand studies of engines: spring and capacitive pressure recorders and thrust recorders, inductive flow-rate sensors and time recorders utilizing magnetoelectric oscilloscopes, etc. LRE devices with automatically controlled variable thrust with constant pressure in the combustion chamber were developed. /85

In 1930, the first LRE developed in the Soviet Union, the ORM-1 laboratory engine was designed.[2]

In 1931, flame testing of engines was begun at GDL. Unitary fuels, solutions of a fuel (toluene or gasoline) in nitrogen tetroxide, were tested in the ORM laboratory engine.[3] The ORM-1, manufactured in 1930-1931, was designed to use nitrogen tetroxide and toluene. Test stand operations were performed with liquid

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[1]A hypergolic fuel is a two-component liquid rocket fuel which ignites at room temperature when the two components contact each other.

Chemical ignition means ignition of the basic fuel in an LRE, in which the basic fuel consists of hypergolic components or a hypergolic supplementary starting fuel is used, introduced to the combustion chamber only during the initial period of operation of the engine.

[2]The basic designation ORM was given to all LRE develcped under the leadership of V. P. Glushko in the GDL and at RNII.

[3]Nitrogen tetroxide is a high-boiling-point oxidizer for LRE. It provides greater specific impulse than nitric acid, but is inferior in the operational respect, since it has a narrower liquid-state storage temperature interval.

oxygen and gasoline, since experiments performed earlier with the ORM showed that it was very dangerous to start the engine with a high-boiling oxidizer, particularly considering the complex shape of the ORM-1 combustion chamber.

In 1932, engines from ORM-4 to ORM-22 were developed, constructed and tested for experimental purposes. Liquid oxygen, nitric acid, nitrogen tetroxide and solutions of nitrogen tetroxide in nitric acid were used as oxidizers. Nitrogen tetroxide was produced on a pilot-scale installation at the laboratory, developed and put in use in 1931. Fuels tested included gasoline, benzene, toluene and kerosene.

During the tests, start-up was developed and the organization of processes within the chamber was improved, and methods were developed for reliable cooling of the combustion chamber.

In 1933, experimental LRE from ORM-23 to ORM-49 were produced at the GDL and used to continue studies of problems of LRE design. In order to create LRE providing sufficiently high specific impulse and operating stably with identical indicators in a series of tests, i.e., reproducibly, reliably and developing the required thrust, it was necessary to select fuel components and the most favorable ratio of components, to develop methods of feeding the fuel to the combustion chamber, and to learn to organize the process of its combustion. This same year, practical LRE were produced -- the ORM-50, ORM-51 and ORM-52, burning kerosene and nitric acid both in pure form and mixed with oxides of nitrogen. These engines used the principle of chemical ignition developed at JPL, i.e., ignition by means of hypergolic fuel. A number of experimental rocket-powered flight vehicles were planned in 1932-1933 to test the engines under flight conditions. /86

2.3. Liquid and Electrical Rocket Engines and Rockets of GDL

The Gas Dynamics Laboratory studied and developed an electric rocket engine (ERE), liquid-fueled rocket engines (LRE), called at that time ORM, and experimental models of rockets, called RLA.

Step by step, the design of the individual elements and of the engine as a whole was improved, which finally led to the creation of a rather good liquid-fueled rocket engine for the time, the ORM-52.

"Of particular promise," wrote M. N. Tykhachevskiy in 1932, "are the experiments at GDL on a liquid-fueled reaction

motor, which has recently been produced in their laboratory."[1]

In the summer of 1932 and in January of 1933, GDL was visited by S. P. Korolev, F. A. Tsander, M. K. Tikhonravov, Yu. A. Pobedonostsev and other leaders and workers of GIRD, who witnessed the operation of the LRE constructed at GDL. Thus were the first meetings between the workers of GDL and GIRD conducted.

Experimental Electric Rocket Engine

K. E. Tsiolkovskiy mentioned the possibility of using electricity to drive rocket engines. In 1933, K. E. Tsiolkovskiy wrote, "The best transmission of energy is transmission by means of electric current. But how can electric energy be converted to mechanical work?... Electric current can be used to produce high temperatures and chemical decomposition of matter."[2] /87

The designer of the world's first operating electrothermal rocket engine was V. P. Glushko.

In 1928-1929, he developed a plan for a space rocket ship -- a heliorocket plane, driven by electric power produced by means of solar batteries surrounding the ship in the form of a disc. In April of 1929, the Military Scientific Research Committee of the Revolutionary Military Council of the USSR received the work "Metal as an Explosive Substance. A Reaction Engine with a High Exhaust Velocity," by V. P. Glushko.[3] This work, a part of his plan, served as a basis for the creation of the electric rocket engine at GDL.

At first, the GDL division involved in the development and testing of ERE (1929-1930) was colocated with the high voltage laboratory of the Institute of Physics and Technology, directed by Academician I. A. Ioffe. The laboratory itself, headed by Academician A. A. Chernyshev, was located at Lesnoy near Leningrad and in 1930 was reorganized as the Electrophysical Institute. In 1932-1933, work on ERE was conducted on the territory of the Ioanncvskiy ravelin of Petropavlovskaya fortress.

The experimental work was preceded by analytic calculation. Then, engines of various types were made and tested; studies of

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[1]"Cosmonautics," Moscow, The Soviet Encyclopedia, 1970, p. 93.

[2]Tsiolkovskiy, K. E., Collected Works, Vol. 2, Academy of Sciences USSR Press, Moscow, 1954, p. 417.

[3]GDL-OKV Archives, d. 1, pp. 1-16.

the properties of various conducting fluids and metals were also conducted in order to determine the possibility of using them as working fluids.

In the Author's Certificate awarded V. P. Glushko, the inventor of the ERE, on 23 March 1931[1], various engine plans were suggested in which the substance for the electric explosion was introduced continually to the chamber. (Electric explosion refers to the rapid conversion of the substance introduced to the chamber to the gaseous state.)

In 1929-1930, two types of continuous-feed systems, called carburetors were developed: a liquid system for a liquid working fluid and a wire system for a wire working fluid.

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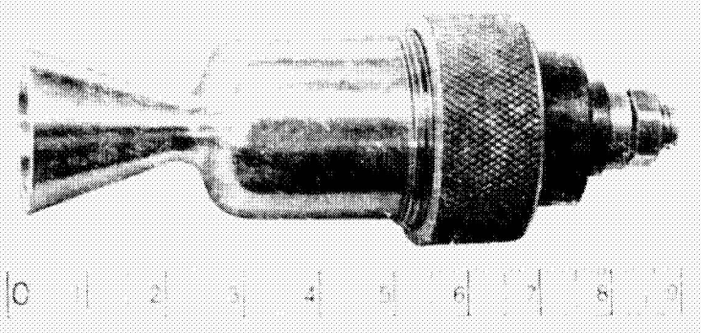

External Appearance of the Electric Rocket Engine (ERE) Designed by V. P. Glushko

In the liquid carburetor, the liquid was supplied from tanks through tubes with interchangeable spray fittings of various diameters. The liquids used included mercury, an aqueous solution of copper sulfate, a weak aqueous solution of nitric acid and other substances.

In the wire carburetor, the feed mechanism consisted of two steel rollers with a guide device. The rollers were driven by an electric motor through a reducing drive. The working fluid used consisted of metal wires of various metals (copper, nickel, tungsten, lead, etc.) and carbon filaments. The frequency of explosions was raised to several dozen per second. The explosions were recorded by a photographic camera through light filters. The gases produced by evaporation of the metal were accelerated in an ordinary nozzle.

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[1]GDL-OKV Archives, d. 3, pp. 24-26, 47.

These ERE were supplied with power by a high-capacity electric pulsing device, the basic elements of which were a high-voltage transformer, four rectifiers and oil-filled condensers with a capacitance of 4 μf, charged up to 40 kv.

The effect of an individual electric explosion was determined (1932-1933) by means of a ballistic pendulum. It was demonstrated that the experimental ERE produced an exhaust velocity of several tens of kilometers per second.

In the early 1930's, the level of science and technology did not allow an effective ERE and compact on-board electric power supply to be created. Therefore, the work on ERE was temporarily interrupted, and V. P. Glushko began working full time on the study and development of LRE. /89

A new stage in the development of electric rocket engines began in the late 40's and early 50's, when achievement in a number of areas of science were found to be sufficient for the development of experimental work in the USSR and the USA. At the same time, in connection with achievements in the area of the study of space, a practical need for ERE appeared.

Modern ERE are made according to various designs.

In an electrothermal rocket engine, the working fluid, solid or low-molecular-weight gas (helium, hydrogen, etc.) is heated to a high temperature by means of an electric arc, ohmic heating or some other method of electric heating. The heated working fluid is accelerated in an ordinary nozzle to velocities of not over 20 km/sec.

A better solution is the electromagnetic (plasma) rocket engine, in which the working fluid is converted to a plasma and accelerated by means of an electromagnetic field acting on the plasma. In these engines, exhaust velocities of hundreds of km/sec can be achieved.

Another modern ERE is the electrostatic (ion) rocket engine, in which the working fluid (cesium, rubidium, mercury, argon, etc.) is first heated until ionized, after which the positive ions formed are accelerated in a strong electrostatic field to velocities of tens or hundreds of km/sec. A special emitter neutralizes the reaction stream with electrons.

In planning ERE, the optimal value of specific impulse is selected, the value of which depends to a significant extent on the weight and power characteristics of the on-board electric power supply, the parameters of the electric current converters and other parts of the installation. In order to produce electric power on board a spacecraft, chemical, nuclear or solar power plants are used. /90

ERE generally develop low thrust, but can operate over long periods of time.

At the present time, electric rocket engines are being used by the USSR for the study of space.

A plasma magnetohydrodynamic ERE was first practically used in the orientation system on the Zond-2 Soviet automatic space probe, launched toward Mars on 30 November 1964.

An electrostatic rocket engine was first tested in orbital flight in 1964 on the Voskhod spacecraft. The first test of an ion engine in flight over a ballistic trajectory was conducted in the USA on 20 May 1964.

In October of 1966, the Yantar'-1 automatic ionospheric laboratory, equipped with an experimental plasma-ion ERE, was launched in order to study the interaction of the reaction jet of an ERE with the ionospheric plasma. The device was carried on a geophysical rocket.

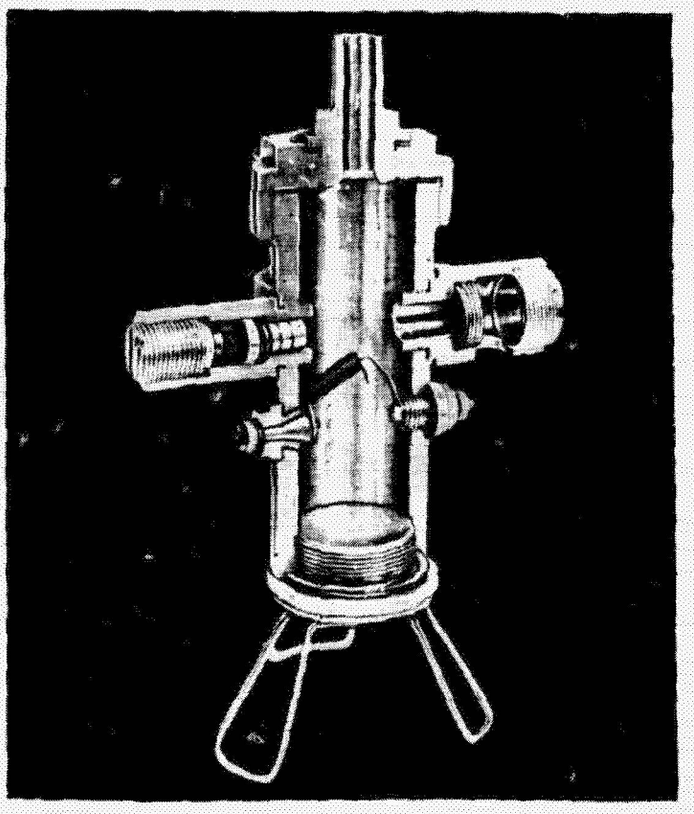
Thus, the developments on ERE performed in the late 20's and early 30's at GDL properly predicted the development of technology and preceded the actual demands of practice in this area by approximately three decades.

Selection of Fuel for LRE

The most important problem to be solved in the creation of LRE is the provision of high energy characteristics of the engine. It is therefore understandable that the first stage of investigations at GDL was the study of fuels, the investigation of various mixture formation plans.

An experimental rocket motor, the ORM, was created for preliminary evaluation of the conditions of ignition and combustion of liquid fuels in a chamber with a nozzle. The ORM consisted of a thick-wall body, a nozzle cover and a screw plug; a membrane was installed beneath the nozzle nut. A safety valve and crusher device were attached to the body, fixing the maximum pressure during the period of combustion. Two contacts screwed into threaded holes in the body carried a pyrotechnical igniter. This experimental model (i.e., the ORM) was developed to test prepared mixtures of oxidizer and fuel and underwent test stand testing in 1931. The charge of fuel to be tested (a mixture of benzene or toluene or gasoline with nitrogen tetroxide) was placed in the combustion chamber. When current was applied, the pyrotechnical composition ignited, igniting the fuel. The pressure of the burning fuel gases ruptured the calibrated membrane, and the combustion products flowed out of the nozzle. If there was no /91

membrane, the chamber was freely connected to the surrounding medium, the beginning of fuel ignition occurred in a semi-open volume under atmospheric pressure.



Cross-Section of Experimental Rocket Motor (ORM)

Tests were performed with nozzles from 3.4 to 12 mm in diameter. In 1931, 46 flame tests of the ORM were performed, the results of which were used to evaluate the suitability of various mixture formation plans for use in LRE. When prepared mixtures were used, explosions were frequent; therefore, separate feed of two-component fuels was subsequently used at GDL. /92

In 1930, GDL first suggested highly concentrated nitric acid, its solutions with nitrogen tetroxide, hydrogen peroxide, perchloric acid, tetranitromethane and other substances as oxidizers, and beryllium and a mixture of beryllium with hydrogen as fuels. Flame tests were performed with nitric acid, solutions of nitrogen tetroxide in nitric acid and liquid oxygen.

Chemical ignition was first suggestedin 1931, then used in a number of models of the ORM. Hypergolic fuels were studied, their corrosiveness for various structural materials was tested, the best methods for production of nitric acid oxidizers were determined and experimental production of nitrogen tetroxide was undertaken to support the laboratory and test stand operations.

Due to the difficulty of producing nitrogen tetroxide in large quantities, the most promising fuel type was found to be highly concentrated nitric acid and kerosene. These components are produced industrially, are not explosive, can be stored for

extended periods and, consequently, allow rockets to be filled long before launching. Nitric acid fuel provided good motor operating stability and high specific impulse for the time

Engines with Annular Combustion Chambers

This series of rocket engines includes the ORM-1, ORM-2, ORM-3, ORM-6-0, ORM-6 and ORM-7, the combustion chambers of which were annular in shape. They were created to study processes inside the chamber and the regularities of changes in thrust and specific impulse upon combustion of fuels in an annular chamber. The annular shape of the chamber was selected /93
partially because it was found to be convenient to maintain constant pressure as the thrust was choked and the fuel components sprayed into the chamber mixed better due to the elongation of their path and rotation in the chamber by 180°.

ORM-1 was developed and constructed in 1930-31. The engine was designed for test stand studies of processes within the chamber and was intended to be used repeatedly for short periods of time. The basic fuel called for by the plan was nitrogen tetroxide and toluene, although the motor was tested with liquid oxygen and gasoline and developed a thrust of up to 20 kg.

The ORM-1 combustion chamber consisted of a cylindrical steel body covered with copper; the mixing head of the chamber, also clad with copper, was made in one piece with the outer body.

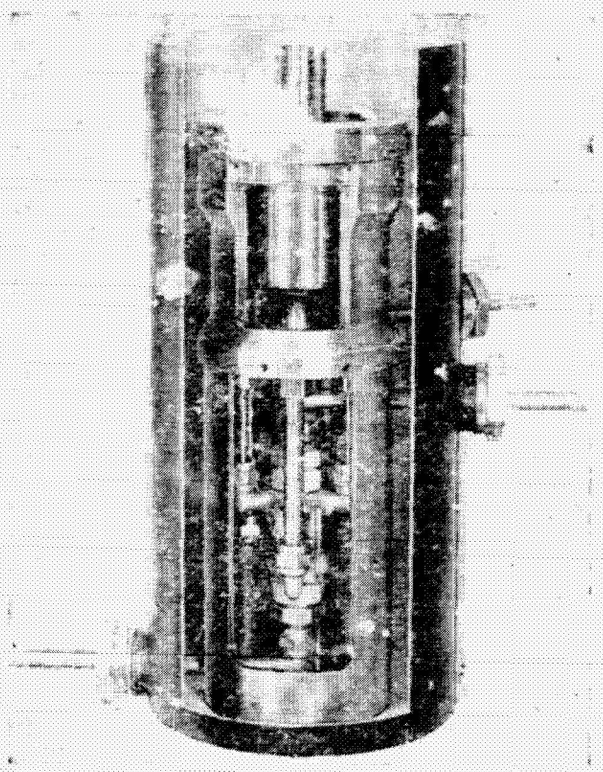
The mixing head, also called the sprayer head, was the device used for mixture formation, i.e., spraying, atomizing and mixing of the fuel components in the combustion chamber. The design of the mixer went far to determine the quality of the engine -- the completeness of combustion, stability of the combustion process, reproducibility and stability of processes within the chamber, etc.

The end cover was attached to the outer body by threading on the opposite side from the head. The point where the combustion chamber and cover were joined was sealed by means of a circular knife seal.

A copper-covered steel nozzle was also threaded to the inner cup. In place of the ordinary conical supersonic nozzle, this nozzle had a rather long cylindrical portion with the diameter of the critical cross section. This design was justified by the fact that the supersonic portion of the nozzle is not required to study processes within the chamber, since the

supersonic stream developing in the expanding portion of the nozzle does not perturb the subsonic stream in the constricting portion of the nozzle and, therefore, does not influence processes within the chamber. Also, manufacture of the engine is simplified by the absence of the expanding portion of the nozzle.

Six jet-type one-piece sprayers (three for the oxidizer, three for the fuel) were welded into apertures spaced around the head of the combustion chamber on a single circle. Ball back valves with screen filters were placed just before the sprayers. The copper surfaces of the sprayers were galvanically coated with gold to make them corrosion resistant. During tests, the motor was submerged in water which filled the cooling jacket. /94



Cross-Section of ORM-1 Liquid-Fueled Rocket Engine

The fuel in the ORM-1 was ignited by the flame of burning cotton, wet with alcohol. The cotton was placed in the combustion chamber before each test, then ignited with a Bickford fuse. The combustion products of the main fuel, formed in the annular space of the chamber, flowed toward the nozzle placed at the center of the engine, changing their direction of motion by 180°. /95

The fuel components were carried in thick-wall tanks and forced into the combustion chamber by compressed gas pressure.

A further development of the design of the ORM-1 engine was the ORM-2 (1931). In contrast to the ORM-1, slit-type sprayers and spark plugs were used, the intensity of cooling of the nozzle fairing and combustion chamber was increased by the introduction of dynamic

cooling, and the design of certain individual parts and sections was simplified. The ORM-2 partially used the same type of cooling as ORM-1, i.e., capacitive cooling (liberation of heat into naturally circulating liquid surrounding the engine), so-called static cooling.

By the time ORM-2 was finished, new and better designs had been developed, and so ORM-2 was never tested.

The ORM-1 and ORM-2 engines were designed for element-by-element testing of some of the main ideas upon which the ORM-3 engine was based. This engine called for maintenance of constant pressure in the combustion chamber with changing thrust, an exponential nozzle, intensive (dynamic) cooling of the combustion chamber by fuel, heat insulation of the combustion chamber on the inside, slit-type sprayers and chemical self-ignition.

The exponential nozzle developed at GDL is a profiled nozzle in which the inner surfaces are given the proper geometric shape to assure optimal flow characteristics of the combustion products. The best contour of the nozzle is that which achieves the extreme of specific impulse.

The methods of calculation of the nozzle were first published in the USSR in 1957 by Yu. D. Shmyglevskiy and L. Ye. Sternin. Simplified profiling methods are frequently used -- the nozzle contour is a circular arc, parabola, exponential curve, etc.

The ORM-3 engine used hypergolic fuel, eliminating the need for special ignition devices. Constancy of pressure in chamber 1 was achieved by moving nozzle 5, sealed around two belts 3 with a hydraulic or pneumatic device. As the nozzle moved, the critical cross section changed, since the relative position of the profiled projection at the center of the head of the chamber which entered the nozzle was changed. In 1930- /96
1931, experimental and design work was continued on the development of individual elements of this engine, in particular using the ORM-1 engine.

The ORM-6 and ORM-7 engines were cooled by the fuel components, had jet-type sprayers and represented further development of the design of annular (slit-type) combustion chambers. They were developed and produced in 1932.

The ORM-3, ORM-6 and ORM-7 engines were not tested, since by that time the data from testing of the ORM-1 indicated that annular combustion chambers were undesirable, as was later confirmed. Actually, the ratio of heated surface (walls) to volume where combustion occurs is greater in an annular

combustion chamber than in a cylindrical chamber; during combustion, the combustion products change their direction of motion by 180°, which does not occur in cylindrical chambers. Both of these factors cause overheating of the walls, particularly the end portion, and complicate cooling conditions. The most significant difficulty is in the organization of processes within the chamber. /97

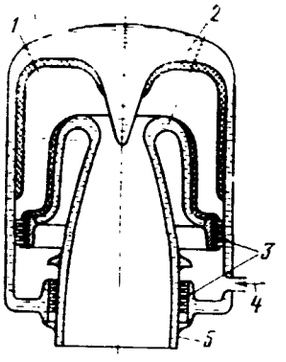


Diagram of Regulation of ORM-3 Engine: 1, Combustion Chamber; 2, Cooling Fluid; 3, Sealing Belt; 4, Controlling Gas or Liquid; 5, Nozzle

Furthermore, the creation of an engine with constant pressure in the chamber but variable thrust was found to be an independent problem of some difficulty.

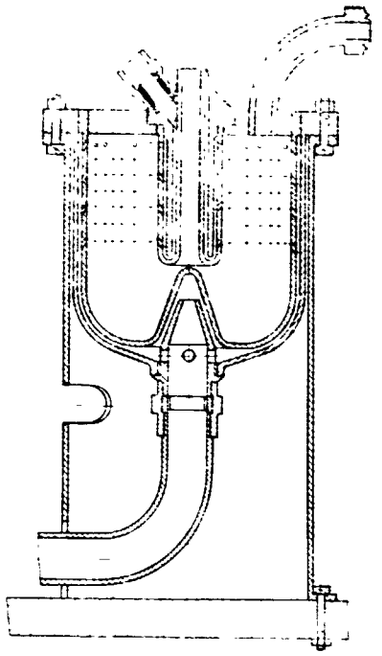
Experiments conducted in 1929-1931 confirmed the possibility of creation of reliable LRE. However, it was also quite obvious that an engine of constant thrust should be created first, requiring that a multitude of new problems be solved; they included organization of high quality mixture formation, provision of complete fuel combustion, assurance of high specific impulse, organization of reliable chamber wall cooling, etc. Therefore, the program of further studies called for stage-by-stage development of design elements and orderly, deep study of the individual processes.

Engines with Radially Placed Nozzles

This group of engines includes the ORM-4, ORM-5, ORM-8, ORM-10 and ORM-13, developed in 1932.

These engines were created to study the processes of mixing of fuel components, ignition, starting and shutdown. In order to simplify the design of the combustion chamber and test stand, to test the engine in the position with the head upward, the nozzle was made in the form of two radially placed apertures opposite each other in the lower portion of the combustion chamber wall.

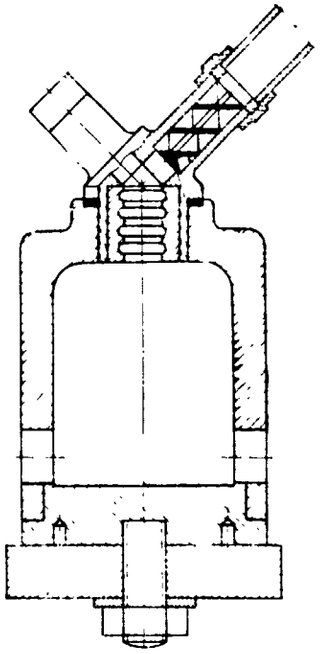
The engines used pyrotechnic or electric-spark ignition, with two spark plugs with massive copper electrodes installed to increase the reliability of ignition. In the first three models of this group of engines, the fuel components were fed directly into the combustion chamber, where they were mixed.



The ORM-6 Engine

The ORM-4, ORM-5 and ORM-8 engines differed from each other in sprayer design, with the sprayers located on the head of the cylindrical combustion chamber: the ORM-4 engine had slit-type sprayers, ORM-5 was equipped with jet-slit sprayers with intersecting streams, while in ORM-8 the components were fed in through jet-type sprayers, also with intersecting streams. In all three models, the thick-wall steel body of the cylindrical chamber was attached by means of a threaded joint at its end to the plate of the test stand. The internal diameter of the combustion chamber of these engines was 40 mm. /98

These engines underwent flame testing in 1932. Liquid oxygen, liquid air, nitric acid, nitrogen tetroxide and solutions of nitrogen tetroxide in nitric acid were used as oxidizers; gasoline, a mixture of gasoline with benzene and toluene were used as fuels.



The ORM-10 Engine

Electric spark ignition was found to be unreliable. Metal-nitrate caps were developed to assure reliable ignition of fuels with high-boiling oxidizers, while trotyl pyroxyl caps, electrically ignited, were used for fuels with cryogenic oxidizers.

These tests yielded valuable material on problems of safe starting and stopping of engines, reliable ignition and start-up when operating with various fuels. The data from testing of the ORM-4, ORM-5 and ORM-8 engines allowed a comparative evaluation of the quality of engines equipped with jet and slit sprayers.

In the basic operating mode, the pressure in the chamber reached several atmospheres, the operating time -- some tens of seconds. During

individual, brief tests, the pressure in the chamber reached 50 atm.

In order to study the possibility of high quality mixing of fuel components in the liquid phase before they were fed to the combustion chamber and atomized, thus increasing the completeness of combustion and the thrust per liter[1], the ORM-10 and ORM-13 engines were planned with prechambers. /99

The fore-chamber or prechamber was a small chamber in which preliminary mixture formation and partial combustion of the fuel components occurred, after which the components were delivered to the main chamber, where combustion was completed.

In the ORM-10, the prechamber was made in the form of an axisymmetrical channel; sections of identical length but different diameter alternated along the length of this chamber, to improve mixing of the components which were fed in through sprayers, the internal cavities of which contained spiral snakes to spin the stream of liquid flowing from the sprayer. The combustion products flowed out through two oppositely placed radial apertures.

In ORM-13, the fuel components were fed in through concentrically placed slit sprayers into an annular prechamber. After mixing, they were then sent to the spherical portion of the prechamber and then, through the expanding portion, into the main combustion chamber, which was cylindrical.

In one version, extra-rich or extra-pure liquid fuel mixture of oxidizer and fuel, incapable of exploding due to its composition, was fed in through one sprayer, while the other sprayer supplied the remaining component required for complete combustion.

The difficulty of manufacturing engines with three chambers, the possibility of overheating of the heads and explosion during start-up, led to new design solutions and stopped the manufacture and testing of the ORM-10 and ORM-13 engines.

However, as we know, prechambers did come to be used in certain engines produced in the first few years after the war, particularly in the engines of the V2A and V5V geophysical rockets. This resulted from the achievement of positive results

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[1]The thrust per liter refers to the ratio of thrust developed by the engine in kg to the volume of the combustion chamber in liters.

in a series of new tests performed with prechambers in the late 30's and early 40's.

Engines with Internal Protective Coatings /100

The results of the preceding tests indicated the need to find new methods to increase the operating time of an engine. It was found that this could be done by coating the inner surface of the chamber with cuprite or application of a refractory heat insulating covering. Furthermore, it was found that the cylindrical shape is the most favorable for a combustion chamber as regards organization of processes within the chamber, cooling and simplicity of production. Further experiments were used to measure thrust and determine specific impulse. Methods of ignition and start-up were improved; a number of types of sprayers were compared to select the best.

The time came to go over to testing of combustion chambers with a supersonic nozzle, since it was known that a nozzle can increase both thrust and, consequently, specific impulse. Only tests of combustion chambers in combination with nozzles should be used to fully evaluate the quality of the engine as a whole and of its individual units. The presence of the nozzle should influence the selection of a method of ignition of the fuel and the motor start-up mode.

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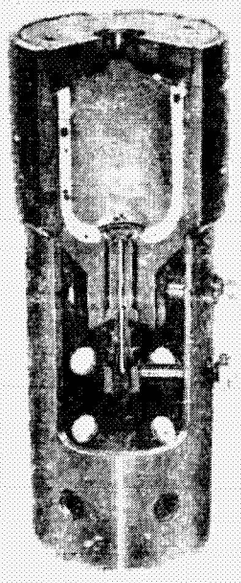
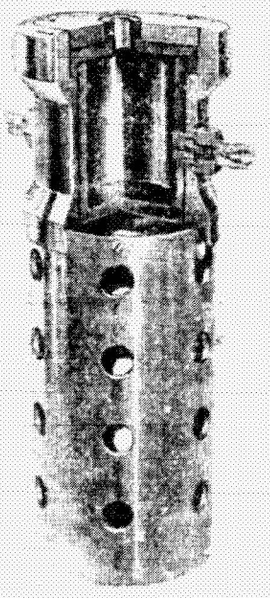


The ORM-9 Engine



The ORM-12 Engine

The ORM-9 engine had a combustion chamber with an internal diameter and height of 90 mm, covered on the inside with a layer of ceramic heat insulation 10 mm thick of zirconium dioxide or magnesium dioxide mixed with binder materials. The nozzle of the engine, located in the flat cover, was clad with a layer of cuprite 8 mm thick; its critical cross section was 15 mm in diameter. The entry to the nozzle was rounded, the exit plane was of the critical cross section. The two-component sprayers were located in the head of the combustion chamber. Fuel (gasoline) entered through a center channel with several output apertures, while the oxidizer (liquid oxygen) entered through a multiple-jet sprayer, the channels of which were located around the central channel, parallel to its axis. The output apertures of the central channel were tilted to make the streams of fuel components intersect. The engine was placed in a steel cup in the test stand and tested with nozzle upward. Several firings of some tens of seconds each were performed in 1932. One of these was visited by Professor V. P. Vetchinkin (TsAGI), who concluded: "The most important part of the work for the manufacture of a rocket -- the production of a liquid-fueled reaction motor -- has been performed at GDL... From this standpoint, the achievements of the GDL (primarily of Engineer V. P. Glushko) must be considered outstanding."[1] /102

In ORM-11, the chamber and nozzle were also clad with cuprite. The sprayers were also two-component jet type sprayers with concentric placement of the fuel-feeding channels. They provided fine, even atomization of the fuel; two-component sprayers were found to be the best and are successfully used in a number of LRE designs today.

The ORM-12 engine had the same dimensions as the ORM-9. The chamber and nozzle in this engine were also clad with cuprite, but the fuel components entered the combustion chamber through individual snake sprayers located opposite each other approximately at the middle cross section of the chamber. Back valves were placed before the entry to the sprayers. The ORM-11 and ORM-12 engines were tested on oxygen-gasoline and nitric acid-kerosene fuels.

The ORM-14 and ORM-15 engines were planned but not manufactured, since their design, similar to certain foreign models, was considered to be clearly unpromising. The primary shortcoming of the engines was the fact that the fuel components were fed into the combustion chamber from the direction of the nozzle rather than toward the nozzle as is usually done.

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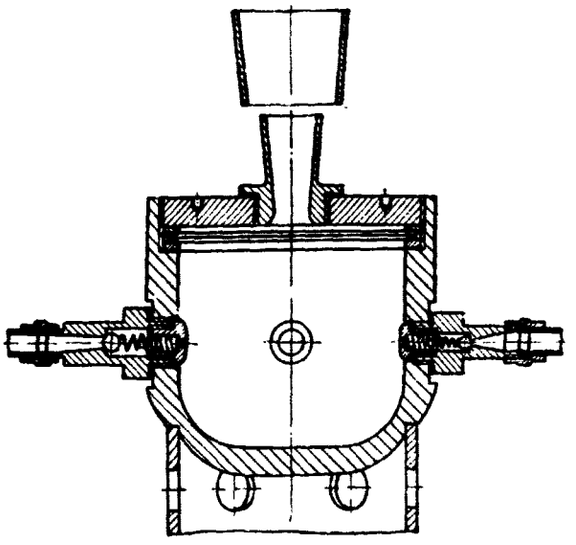
[1] "Cosmonautics," Moscow, The Soviet Encyclopedia, 1970, p. 93.

The next model was the ORM-16 engine. It has a supersonic conical nozzle. The fuel entered the chamber through an improved centrifugal sprayer. ORM-16 underwent flame testing in 1932.

The ORM-17-ORM-21 engines, developed in 1932 on the model of the ORM-16, differed only in length of cylindrical portion of the combustion chamber and were designed to study the influence of chamber volume on processes within the chamber.

The ORM-23 engines with two centrifugal sprayers, the delivery of which was regulated by a hydraulically moved needle, had a combustion chamber placed between the sprayers and could be repeatedly started. An air-gasoline mixture was fed to the chamber and ignited by two spark plugs. This engine was successfully tested with nitric acid fuel in early 1933. /103



The ORM-16 Engine

The centrifugal sprayer, first used by GDL in rocket engine construction, allowed a significant improvement in the quality of LRE and practically almost completely solved the problem of preparation of the fuel for complete combustion. In centrifugal sprayers, the fuel components, fed under pressure, are twisted as they pass through a nonmoving multipass spiral in the inner cavity of the sprayer or by tangential injection of the liquid into the inner cylindrical cavity of the sprayer. As they fly from the sprayer into the combustion chamber, the components form a so-called atomization cone, consisting of a thin film which rapidly breaks down into tiny drops of various diameters. This new sprayer, used on the ORM-12 and ORM-16, assured fine atomization of the components and good mixing and, as a result, complete combustion of the fuel. Due to this property, spiral sprayers later became widely used and were firmly fixed in domestic rocket engine construction. /104

At the same time, it was established that even when ceramic heat insulation is used, the operating time of a rocket engine is quite limited, and that it is more promising to use copper

alloys with good heat conductivity for the manufacture of nozzles, particularly in the area of the critical cross section.

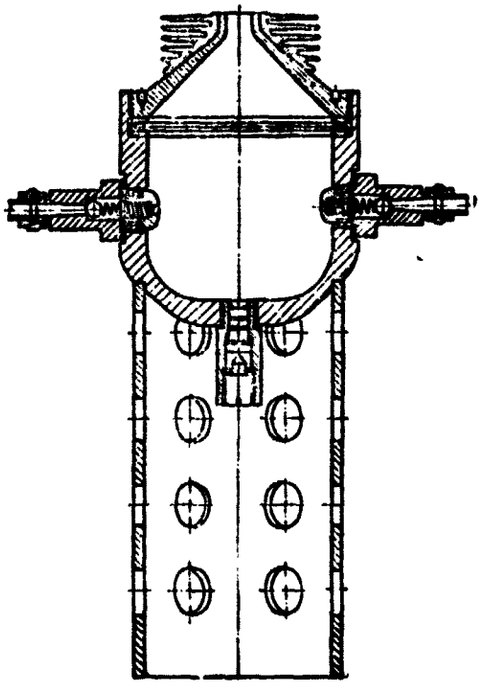
However, in either case unchanging design temperature of the chamber wall can be achieved only if a portion of the heat is carried away from the outer surface of the wall. Therefore, studies of combustion chambers and nozzles cooled from without were planned.

Engines with External Cooling

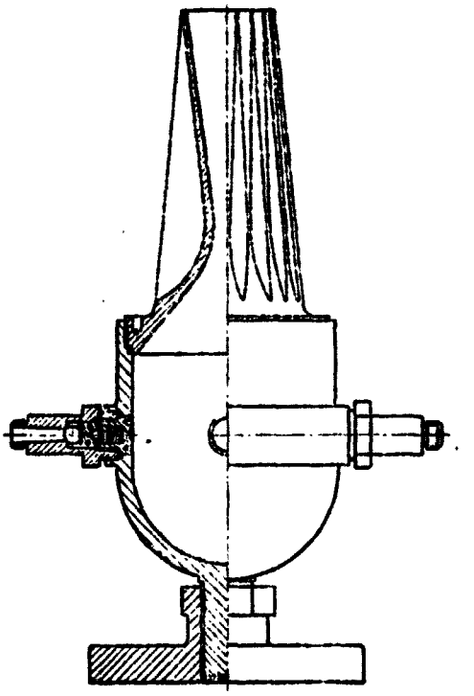
A. Air Cooling

This series includes the first LRE beginning with the ORM-24 developed and tested in 1933. Experiments with preceding engine models confirmed the need to equip the LRE with a cooling system which would carry the heat away from the walls of the chamber continuously during its entire operating time to provide stable thermal conditions for the engine.

/105



The ORM-24 Engine

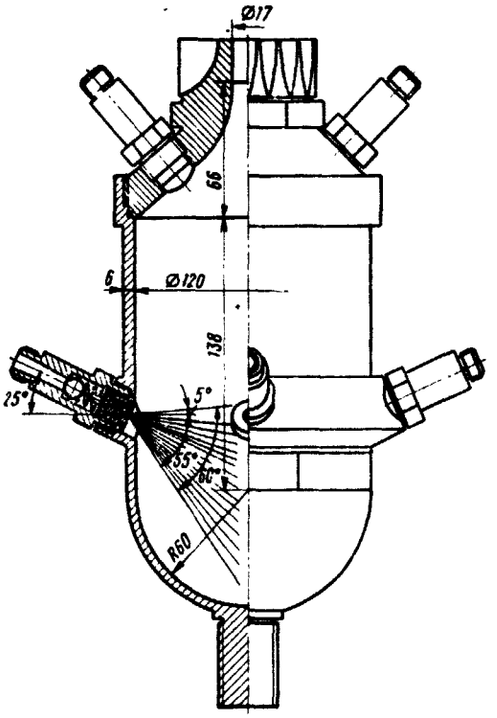


The ORM-26 Engine

At first, attempts were made to cool the engine with an air stream. Therefore, the ORM-24, ORM-25, ORM-26 and ORM-30 engines were made with air-cooled nozzles. The chamber of the

ORM-24, like the ORM-16, was cylindrical in shape; the subsonic portion of the nozzle was conical and ended in a flat nozzle of critical diameter. The upper portion of the nozzle carried a ribbed cuprite radiator. Spiral sprayers with ball back valves were used to feed the fuel components. At the center of the head was a device to determine the maximum pressure in the combustion chamber.

ORM-26 had a shaped nozzle with a well-developed supersonic portion and longitudinal external fins to cool the air stream drawn by the gas stream of the operating engine. The cooling fins encompassed both the subsonic and the supersonic portions of the nozzle. The ORM-29 and ORM-30 engines had massive, short nozzles with air cooling. In ORM-30, the inner surface of the nozzle was not coated and was protected from rupture by a film along the wall created by additional fuel sprayers installed at the entry to the nozzle. This method of heat protection of the nozzle walls was found to be effective and has been widely used in practice. /106



The ORM-30 Engine

Tests of the ORM-24, ORM-25, ORM-26, ORM-29 and ORM-30 engines showed that air cooling could not provide for long-term operation of nozzles.

B. Liquid Cooling /107

An external dynamic liquid cooling system is capable not only of assuring reliable operation of the engine, but also of improving the conditions of processes within the chamber due to the heating of one of the fuel components in the cooling cavity.

The first representatives of such engines -- ORM-2 with fluid cooling of the head by fuel and ORM-5, ORM-6-0, ORM-6 and ORM-7 -- had practically complete cooling by the oxidizer and fuel. Due to the difficulty of manufacture of engines with fluid cooling and the necessity in the first stage of repeated short-term

start-ups to develop fuel spraying and ignition systems, start-up and shut-down modes, the development of a reliable cooling system for long-term operation was delayed to the second stage. Element-by-element development of engines accelerated its creation.

ORM-27 is also a fully cooled engine. The nozzle of ORM-27 had longitudinal finning; the combustion chamber had external fluid cooling. The internal wall was made massive and had an elongation temperature compensator.

Beginning with model ORM-34, all nozzles of engines developed had flowing fluid cooling. In ORM-34, the region of the critical cross section of the nozzle was cooled by liquid flowing through a line at insufficient speed. In order to improve cooling, the contour of the fluid-carrying portion of ORM-35 was somewhat improved, and the speed of the liquid was increased. The nozzle of ORM-39 had an initial section with transverse finning, cooled by liquid. The fully nitric-acid-cooled nozzle of ORM-40 was found to be more stable in tests. In ORM-40, the cooling fluid flowed in a spiral pattern through a thin cooling jacket over the ribbed nozzle wall. Heat transfer from wall to cooling fluid was increased by further increasing the flow speed and its turbulization, a result of the ribbing in the flow line.

As the design of ORM-series engines improved, the pressure in the combustion chamber and specific impulse increased, and it became possible to increase the operating time and thrust of the engines. For example, ORM-39 and ORM-40 developed thrusts of 100-150 kg. The critical cross section of the nozzles of these engines were 25 mm in diameter, the pressure in the combustion chamber reached 20-25 atm. /108

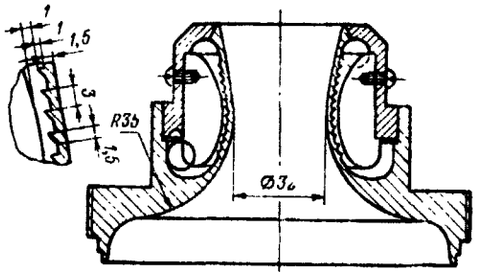


Diagram of External Liquid Cooling of ORM-44 Nozzle

The nozzle of ORM-44 and all subsequent engines had spiral ribbing, washed with nitric acid. In these designs, in order to give the fluid-carrying portion the necessary shape, a split aluminum insert was installed. A gap was formed between the outer surface of the nozzle wall and the inner surface of the insert, through which the cooling fluid flowed. The diameter of the critical cross section of the ORM-44 nozzle was 32 mm. The engine developed a thrust of 250 kg. The ORM-45 and ORM-46 engines,

designed for the same thrust, were sealed by the temperature expansion of the nozzle.

The combustion chambers of all the engines mentioned from ORM-34 to ORM-46 were cylindrical in shape with an internal diameter of 120 mm and were cooled from without by the fuel components, fed by centrifugal spray pumps.

The ORM-47 engine utilized four supercritical mechanically controlled centrifugal sprayers with back valves and filters. Studies performed with ORM-48 allowed the concepts of the nature of the distribution of pressure over the length of the nozzle to be refined. The experimental installation on which this engine was tested was simple and quite convenient; these installations were later widely used in scientific research organizations and educational institutions.

The ORM-49 engine had centrifugal sprayers with plate-type back valves. In order to assure soft start-up of the engine, some of the output apertures of the sprayers were sealed with low-melting Wood's alloy. /109

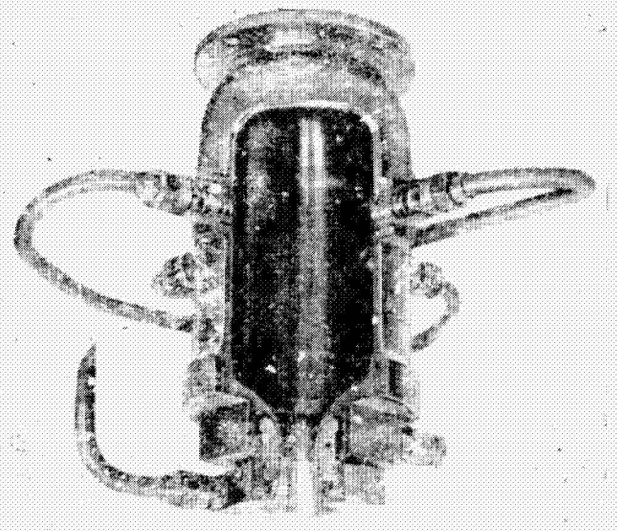
Ignition in the ORM-24 and immediately subsequent engines was by 7-second metal-nitrate pyrotechnic caps, suitable for all oxidizers. Furthermore, in 1933 5-second chlorate caps 40 mm in diameter and height, consisting of 50% Berthollet's salt and 50% sugar were developed, which left no residue upon combustion and were also suitable for all oxidizers. The chlorate caps were also suitable for chemical ignition, since they ignite spontaneously upon contact with nitric acid. These caps were used in 1933 in a number of ORM-series engines for chemical ignition by early oxidizer feed upon engine start-up. Starting in mid-1933 (ORM-44, ORM-50, etc.), chemical ignition was provided using a start-up fuel developed at GDL which ignited spontaneously when mixed with nitric acid. This fuel included a solution of phosphorus in a mixture of carbon disulfide and turpentine. The hypergolic fuel was first carried in a starting tank on the main fuel line near the entry to the combustion chamber; later, it was supplied only through the lines feeding the kerosene sprayers.

Chemical ignition, developed and [illegible] used at GDL, later became common in rocket engine construction.

GDL Engines for Flight Vehicles

The result of the scientific research and experimental design development at GDL prior to 1933 was the creation of the ORM-50, ORM-51 and ORM-52 rocket engines.

Before describing the operation and design of these LRE, let us recall the course of planning-design and experimental work involved in the creation of engines at GDL, briefly described in the preceding sections. The work was begun in 1929 with the development of equipment for test stand measurement of the basic characteristics of LRE. This was followed by selection of fuel components, test-stand studies and selection of a basic diagram of an engine with separate feed of the fuel components. After this, element-by-element, stage-by-stage development of LRE followed. Our attention is drawn by the logical sequence of the change and improvement of designs, the broad range and expediency of the solution of problems involved in the creation of engines of this class. We should also note the extensive experimentation conducted, since only the test stand could give correct answers to the many questions which arose in the design of the first LRE. /110



Cross Section of ORM-50

The development of all ORM began with calculation. The use of the laws of thermochemistry and classical thermodynamics allowed the thermal characteristics of fuels as well as the basic characteristics of the engines such as thrust, pressure in the combustion chamber and along the nozzle, fuel component consumption as a function of engine efficiency, dimensions of critical and exit plane cross section of the nozzle to be determined. The accuracy of these calculations depended on the reliability of determination of the thermal constants of the fuel components and their combustion products and did not result in significant errors. These calculations were performed by V. P. Glushko in 1929-1933 for the engines which he developed, and improvement of calculation methodology was a subject of significant concern. The methods themselves were outlined in a series of lectures read by V. P. Glushko in 1933-1934 at the Zhukovskiy Military Air Academy to two series of students specializing in rocket technology, and also were published in articles and books.[1] /111

[1]The Pioneers of Rocket Technology. Vetchinkin, Glushko, Korolev, Tikhonravov, Selected Works, Moscow, 1972.

The situation was quite different at that time as concerns reliable calculation of liquid fueled rocket engine cooling systems. In his report, "Heat Losses and Cooling of RM," published by V. P. Glushko on 2 July 1931[1], the author presents the results of theoretical and experimental work on the cooling of ORM performed at GDL up to that time. The report presents a method for calculation of the cooling of the ORM combustion chamber, and the author notes that "the nature of thermodynamic calculation of cooling of rocket engine combustion chambers with liquid is well known. However, the problem cannot be solved by theoretical calculations for a single specific case in which heat transfer from the gas to the internal wall occurs at the pressures and temperatures which are found in rocket engine combustion chambers. Our lack of knowledge of the heat transfer coefficients makes the cumbersome thermodynamic calculations useless and forces us to turn to experimentation as the only satisfactory method for solution of these problems."

Actually, we know that overestimation of the accuracy of analytic calculation of cooling systems resulted in destruction of both of the LRE of F. A. Tsander (OR-2 and 10) during their first test stand operation (in 1933).

The cooling system developed at GDL by the experimental method allowed engines to be operated repeatedly.

The ORM-50 engine was developed at GDL for the 05 rocket, planned and built at GIRD.

The ORM-50 engine burned nitric acid and kerosene, had a relatively short, spirally finned, oxidizer-cooled nozzle producing a gas pressure at the exit plane of 1 atm. The /112
liquid oxidizer heated in the cooling jacket was fed to two spiral sprayers, placed radially on the cylindrical portion of the combustion chamber. The fuel entered the chamber, also radially, through two centrifugal sprayers. All sprayers had back valves. The middle cylindrical portion of the combustion chamber had no external liquid cooling, but was cooled by an internal curtain; ignition was chemical.

The ORM-50 engine, of which a single model was built, passed three refinement, operating life and acceptance stand tests in 1933. Then, in 1934, five test launches of the 05 /113
rocket were conducted, powered by this engine, to test the fuel feed system.

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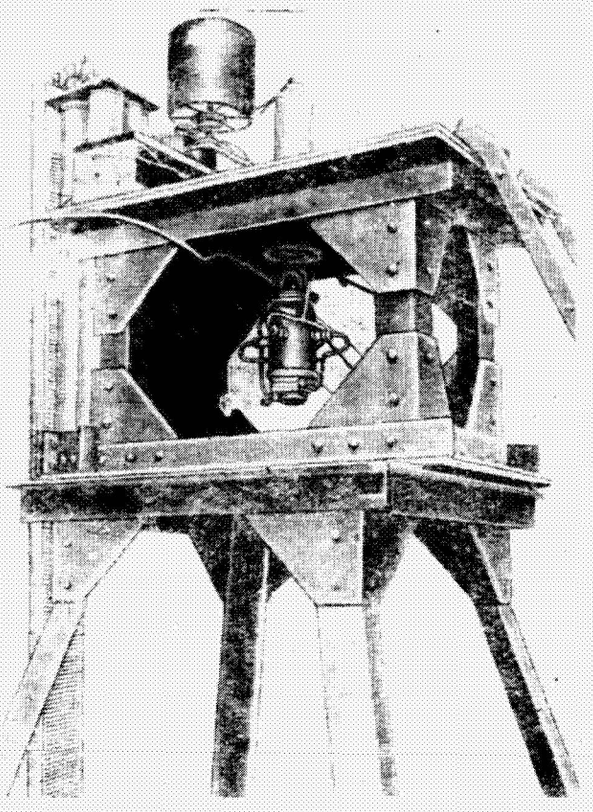
[1]The Pioneers of Rocket Technology. Vetchinkin, Glushko, Korolev, Tikhonravov, Selected Works, Moscow, 1972, pp. 208-212, 770.



The ORM-50 on the Test Stand

When the 05 rocket was launched on the firing range in Moscow, low fuel feed pressure from the tanks caused the engine to develop less than full thrust (design thrust 150 kg) and the engine operated for 60 seconds in the launch stand until the tanks emptied, without lifting the rocket. We should note particularly the viability of the engine, which survived 10 starts.

The experience gained in developing the ORM-50 was used in the creation of a more powerful model -- the ORM-51 engine, designed to develop 250 kg thrust. In the ORM-51 engine, the fuel components were delivered to two circular collectors, located above the hemispherical head of the combustion chamber, after the oxidizer passed through the nozzle cooling jacket. From the collectors, the oxidizer and fuel were sent to six centrifugal sprayers located around the base of the hemisphere and directed upward at an angle of 25°.

Further sicentific research and experimental development resulted in the creation of the ORM-52 engine which, like earlier models, burned nitric acid-kerosene fuel. It was designed for the RLA-1, RLA-2 and RLA-3 rockets planned at GDL, intended to be used both for marine torpedos and as a takeoff booster for the I-4 aircraft. Official tests of the ORM-52 were conducted in 1933. With a combustion chamber pressure of 20-25 atm, it developed a thrust of up to 250-300 kg. An ORM-52 manufactured and tested on the stand in 1935 developed a thrust of 300-320 kg with a feed pressure of 35 atm, a pressure in the combustion chamber of 20 atm and a specific impulse of 210 sec, and was still operating after 29 starts and a total operating time of 533 sec.

In this engine, the steel cylindrical combustion chamber (inside diameter 120 mm) with spherical head had a conical nozzle. The fuel components were fed in through 6 centrifugal sprayers -- three for each component. Back valves were placed before each sprayer. Ignition was chemical, using hypergolic fuel consisting of the basic oxidizer, nitric acid, and a starting fuel -- an active liquid poured into the fuel line from a feeding collector ring before the start. /115

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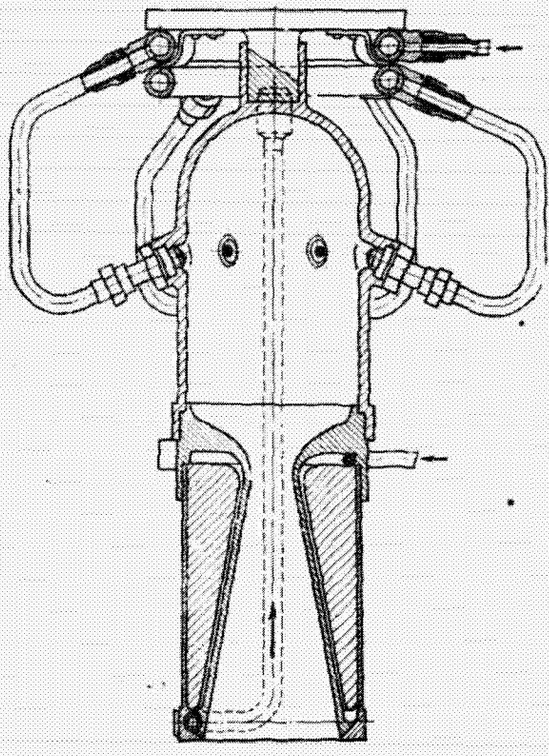
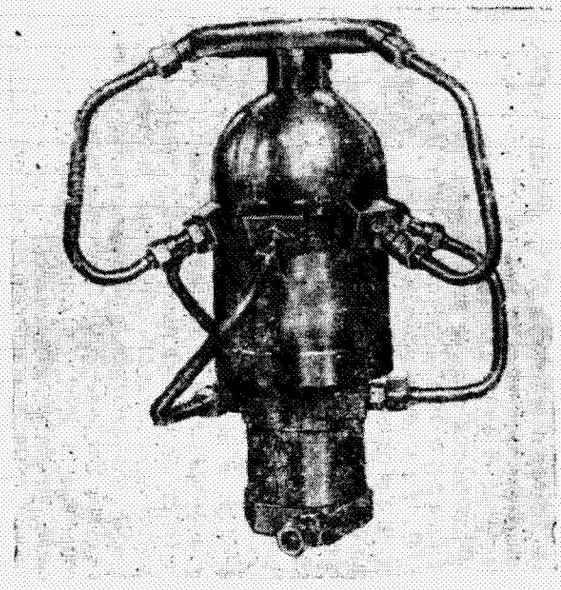




The ORM-52 Engine

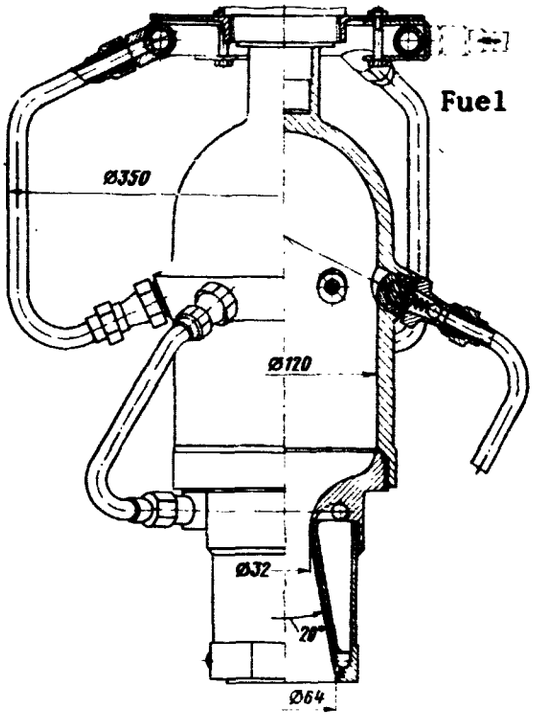
The ORM-51 Engine

The combustion chamber had no external liquid cooling, but was cooled by an internal curtain. The nozzle was cooled with nitric acid, fed from the tank to a collector in the lower portion of the nozzle cooling jacket. The liquid flowed from there through the gap between the jacket and the nozzle, then flowed along the finned nozzle through a spiral channel and exited through three connections, each of which was connected to one of the sprayers. The nozzle was surrounded by a properly shaped aluminum sleeve to provide the correct nozzle shape and size.

The ORM-52 was the best engine of the time as concerns its basic characteristics -- thrust, specific impulse and operating life. /116

Fuel Feed Systems and Stands

Beginning in 1929, together with the search for efficient combustion chamber designs, work was performed on the creation of stand measurement and fuel component feed systems. In 1930, based on analysis of weights, it was established that the most efficient type of fuel feed for low-thrust LRE is an extractive (cylinder) system, using either compressed gas from a pressure accumulator or liquefied gas evaporated in an evaporator. It was clear in the 30's that a pump feed system was preferable for high-thrust LRE. Let us recall that K. E. Tsiolkovskiy planned this type of fuel feed system in his theoretical studies.



Cross Section of the ORM-52 Engine

The development of compact turbine-pump units and the application of the latest structural materials has allowed pump feed systems to be used not only in large engines, but also in LRE producing relatively low thrust, in recent years.

At GDL, a feed system was developed both for flame test stands and for engines installed in flight vehicles of various types. In 1930-1932, LRE were tested at GDL on a stand in which the fuel components were driven from their tanks by compressed nitrogen. The test stand containers for oxidizer and fuel were large-caliber artillery cartridges, lined on the inside with aluminum if they were to contain nitric acid or other corrosive fuel components.

The 20-liter liquid oxygen tank was placed in a sealed brass jacket, made from the cartridge of a 12-inch shell; the gap was filled with carbon dioxide and activated charcoal. When the tank was filled with liquid oxygen, the gaseous carbon dioxide was frozen, and the other gaseous products

present as impurities were absorbed by the charcoal, creating a high vacuum to insulate the tank. /117

During 1931-1932, work was performed at GDL on a special fuel feed system using piston pumps. In 1931, a fuel feed system was developed using a piston unit consisting of four double-acting piston pumps placed radially around the combustion chamber. This pumping unit was planned for use with ORM-3.

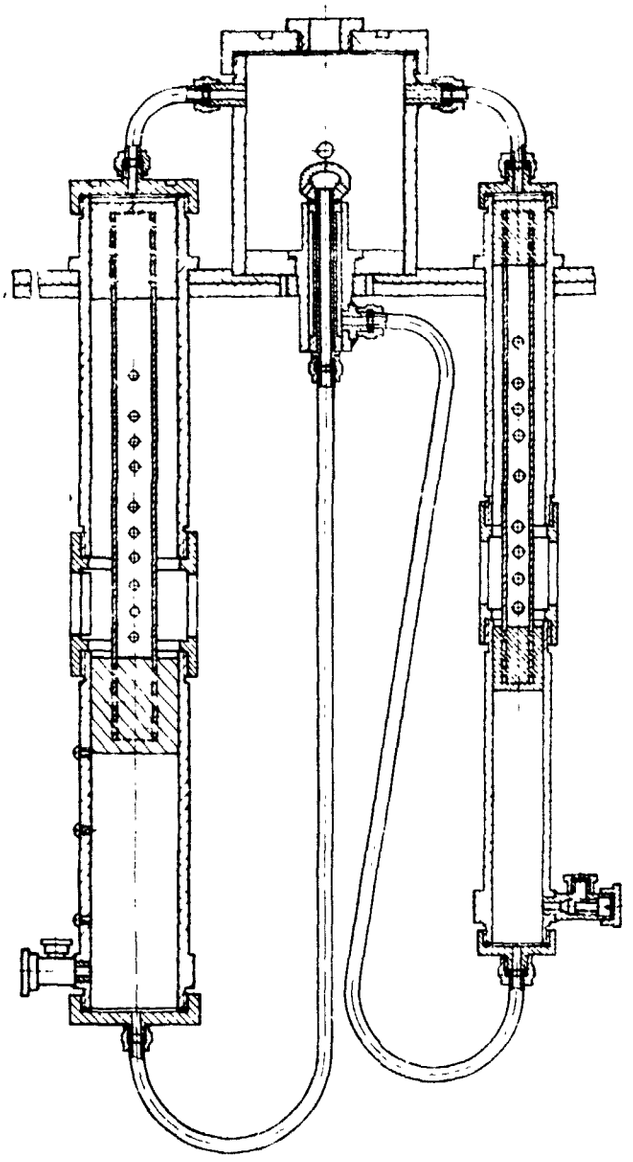
In 1931, the ORM-A engine was constructed according to a plan suggested by B. S. Petropavlovskiy. This engine had a pumping unit driven by the combustion products; a charge of smokeless trotyl pyroxylin powder was burned in the chamber for the first few seconds in order to produce the products for engine start.

In 1931-1932, a piston pumping unit was developed, manufactured and tested to feed a nitrogen tetroxide-toluene engine with a thrust of 300 kg.

One common feature of pump fuel feed systems is the use of a portion of the energy of the gases in the combustion chamber, causing a certain increase in the efficiency of the entire engine. However, these systems have been found practically inconvenient, primarily due to the unevenness of fuel feed during the course of one cycle. Therefore, in 1933 the development was begun of a turbine-pump unit for a nitric acid-kerosene engine developing 300 kg thrust with a fuel componet feed pressure of up to 75 atm (shaft rotation speed 25,000 rpm). A design plan was selected for the TPU [turbine pump unit], consisting of a gas turbine with one stage and two single-stage centrifugal pumps (for oxidizer and fuel) seated on a common horizontal shaft.

The vanes had bidirectional input to relieve the axial forces. The body and vanes of the pump were made of an aluminum alloy. The turbine was powered by the combustion products of the fuel at a temperature of 500° C and a pressure of 15 atm.

During testing of an experimental model at a test stand of the metal plant, a single-stage pump produced a guage delivery pressure of 75 atm, which many had considered impossible at the time. The gas turbine rotor was taken from a supplementary marine engine. According to an air force order (1932), this TPU was designed to be installed together with a 300 kg-thrust combustion chamber on the I-4 aircraft. /119



A Diagram of the ORM-A

The Rocket of GDL /118

In 1932, 1933, RLA rockets were produced at GDL for flight testing of LRE -- the RLA-100, RLA-1, RLA-2 and RLA-3. They were preceded by development of individual RLA systems.

The basic design parameters of the RLA-100 rocket, the plan for which was developed in 1932, were as follows. Flying altitude -- up to 100 km, launch mass -- 400 kg, fuel mass -- 250 kg, engine thrust -- 3000 kg, payload mass -- 20 kg, operating time -- 20 sec. The rocket consisted of two steel bodies interconnected by the nose portion.

Nitric-acid LRE 2 was installed above the center of gravity of the rocket on a gimbal support, was gyroscopically stabilized and served not only as the driving power source, but also as the actuating element of the control system. The nose portion of the rocket 1 carried weather instruments, a parachute and an automatic device for ejection of the instruments after completion of the flight test program. The fuel components were fed into the engine using an extractive system through the hollow gimbal rings, which were sealed into the journals around them. The lower portion of the rocket body 4 carried a compressed gas cylinder, the upper portion 3 carried the fuel tanks, while the nose portion 1 carried the oxidizer

tanks. The duralumin fins 5 in the tail portion of the rocket assured that its center of lateral resistance was lower than the center of gravity.

A test stand with a gimbal support was made to test the engine and determine the stabilizing influence of the exhaust stream. Working drawings of a motion picture camera with a time recording system to be installed in the tail section of the rocket in order to determine the trajectory of flight of the rocket were developed. In 1932, three rocket bodies were under construction at a machine building plant.

The RLA-1, RLA-2 and RLA-3 rockets were designed for flight testing of LRE with up to 250 kg thrust. They were to /120
fly vertically to altitudes of 2 to 4 km. The design of these rockets called for rigid mounting of the engines in the tail portion of the rocket. The fuel feed system was extractive using compressed gas from a pressure cylinder. The fuel tank was located concentrically within the oxidizer tank. The launch was to be vertical, without a guiding support, from a launching stage.

The simplest design was that of the RLA-1 rocket, with the ORM-47 LRE. The body of the rocket was steel, but its nose portion and tail fins were made of wood. The extractive feed system had no pressure reducer. The length of the rocket was 1880 mm, the diameter of the body -- 195 mm.

The RLA-2 rocket, like the RLA-1, was uncontrolled, but differed from the RLA-1 in that it had a duraluminum nose cone, in which were located a parachute and weather instruments, and an automatic device for opening and ejection of the parachute; furthermore, the central portion of the rocket body carried an equipment section with a pressure reducer, assuring even fuel feed to the combustion chamber; the rocket had duraluminum tail fins. These rockets were manufactured in the shops of the National Mint. Preliminary test stand operation of the RLA-2 rocket with the ORM-52 engine (not shown on the figure) was conducted in 1933. /122

The RLA-3 rocket was a controlled rocket, and differed from the RLA-2 in that the body contained an instrument section with two gyroscopic devices with air pressure power (gyroscopes from a marine torpedo were used); they controlled two pairs of rudder fins at the tail of the rocket by means of pneumatic servo drives and mechanical linkages.

Munk aerodynamic profiles were selected for the rudders, providing the minimum displacement of the center of pressure upon movement of the rudders. The RLA-3 was never completed.

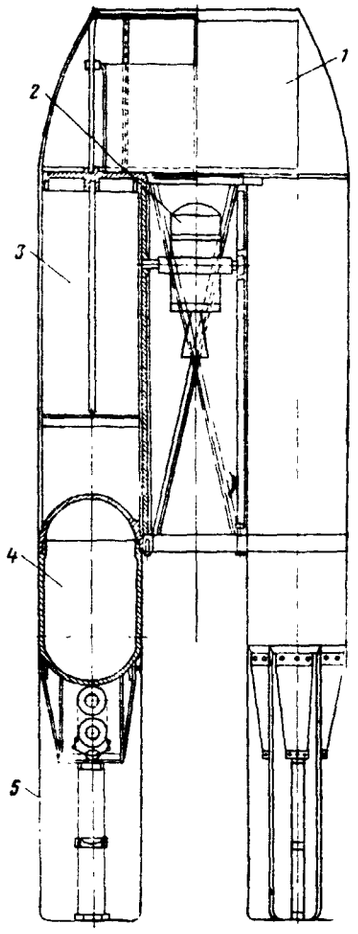
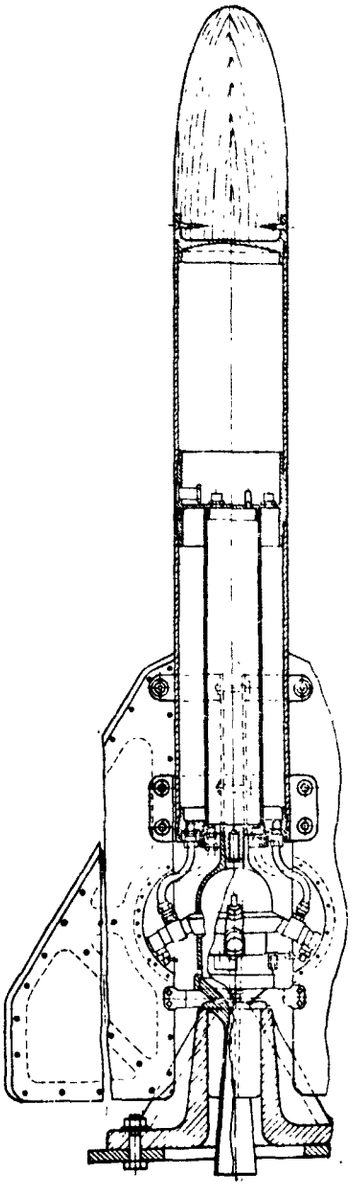


Diagram of the RLA-100 Rocket

In early 1934, the documentation and materials section of the RLA project was transferred to RNII, where a section for development of liquid-fueled rockets was set up. Since by this time RNII already had an approved plan of operations, the RLA rockets were never developed further.

Thus, the basic result of the scientific research and experimental-design work performed at GDL in 1929-1933 was deep and comprehensive study of the processes occurring in LRE, the development of good, economical and reliable engines (for the time) and the solution of a broad range of problems related to rocket engine contruction. Liquid rocket fuels were developed and studied, as well as methods of fuel feed to the combustion chamber, conditions of mixture formation and preparation of fuels for combustion, and methods and means were developed for pyrotechnical and chemical ignition in engines, as well as the start-up and shut-down of engines, processes within the combustion chamber were studied, methods of cooling of combustion chambers were developed, the conditions of flow of the combustion products from nozzles of various shapes were studied, and factors influencing the thrust and specific impulse were determined. Finally, GDL mastered techniques of experimentation and operation of LRE, developed test stand equipment and apparatus for recording of parameters during testing and developed the design of engines developing thrust up to 300 kg with specific impulses of up to 210 sec at ground level with repeated start-up capability.

The viability of LRE was convincingly proven by extended, reliable and economic operation of the ORM-50 and ORM-52. The path was shown for further improvement of engines. The creation /124 of these models was of decisive significance for further development of Soviet rocket engine construction.



D[illegible]gram of the RLA-1 Rocket

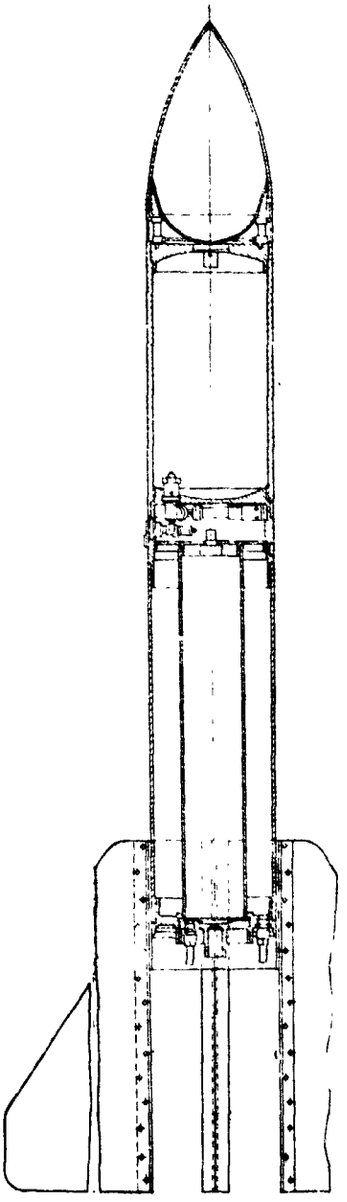


Diagram of the RLA-2 Rocket

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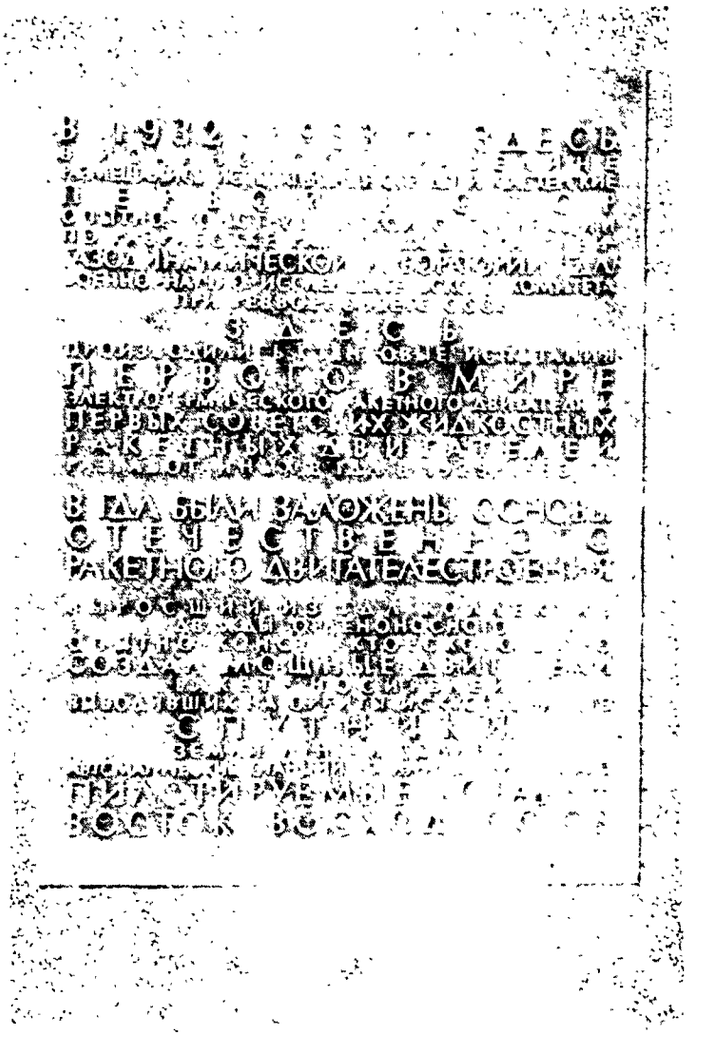

Memorial Plaque Installed on the Building of the Ioannovskiy Ravelina of Petropavlovskaya Fortress. [Translation of Plaque:

In 1932-1933, here at Ioannovskaya Ravelina were located the test stands and shops of the USSR's first experimental-design organization for the development of rocket engines -- the Gas Dynamics Laboratory (GDL) of the Military Scientific Research Committee of the Revolutionary Military Council, USSR. Here were conducted test stand operation of the world's first electrothermal rocket engine and the first Soviet liquid-fueled rocket engines, developed by GDL in 1929-1933. GDL laid the foundation for domestic rocket engine construction. The team which grew out of GDL, a part of the twice awarded Experimental-Design Bureau, created the powerful engines of the booster rockets which placed satellites in orbit around the Earth, moon and sun, sent automatic spacecraft to the moon, Venus and Mars, and launched the manned spacecraft Vostok, Voskhod and Soyuz.]

It has been 44 years since the subdivision for development of ERE and LRE was created at GDL (1929-1933), beginning the long and difficult path of development through subdivisions in RNII (1934-1938) to the formation of the independent group (1939-1940), which in 1941 was expanded into the Experimental Design Bureau. This was the creative path of development from GDL to Experimental Design Bureau of the organization called GDL-OKB. The foundations of domestic rocket engine construction were laid down at GDL. Most of the workers who held creative positions in the twice-awarded Experimental Design Bureau GDL-OKB, which created the powerful liquid-fueled rocket engines for all Soviet booster rockets which have flown in space, came from these walls.

V. P. Glushko, the great leader of GDL-OKB, was the designer of these engines.

In celebration of the 40th anniversary of GDL-OKB (1929-1969), memorial plaques were installed on the buildings of the Main Admiralty and the Ioannovskaya Ravelina of Petropavlovsk Fortress (Leningrad), where GDL was located in the 1930's when the ERE and LRE were invented.

2.4. The Moscow Group for the Study of Reaction Motion, CS Osoaviakhim USSR (MosGIRD)

By the early 1930's, efficient forms of participation of society in the solution of practical problems of astronautics had been found. Party and state organizations provided great aid to individual clubs and groups involved in the study of reaction equipment.

A significant step in development of work on rocket technology in the USSR consisted of the organizational measures performed by Osoaviakhim USSR, which cooperated greatly in the development of new military technology.

From the very beginning of the activity of Osoaviakhim, its theme and structure included the conduct of scientific research work, which was then broadly developed. In particular, the Scientific Research Center of the CS Osoaviakhim included the Bureau of Air Technology (BVT), the task of which included scientific research work and the development of new types of flight vehicles. Design bureaus, shops and laboratories were set up for this purpose. /125

In particular, serious attention was given to the study of problems of rocket technology, based on the works performed since 1921 in the laboratory of N. I. Tikhomirov, and somewhat

later in the sections, clubs and societies of rocket technology enthusiasts.

The first public group for the study of reaction motion began forming in Moscow in connection with the works of F. A. Tsander, who was discussed above. In December of 1930, working at TsIAM, F. A. Tsander attempted together with CS Osoaviakhim to create such a group of rocket technology enthusiasts which could solve independently the great scientific research problems and perform the necessary planning and experimental work.

On 18 July 1931, the first meeting of the new Osoaviakhim organization, called the Bureau for the Study of Reaction Motion (BIRD), was held, under the chairmanship of F. A. Tsander. The plan for the work of BIRD called, in particular, for organization of BIRD cells at enterprises, and a report by F. A. Tsander at a general meeting of members of cells on the conditions of interplanetary voyages.

Thus, BIRD, which later grew into GIRD, was a fully formed organization by this date (18 July 1931).

The name GIRD is first encountered on 20 September 1931 in a letter by one of its members, comrade Fortikov, to K. E. Tsiolkovskiy, who was familiar with the practical and organizational affairs of GIRD.

According to another point of view, GIRD was founded on 18 August 1931, on the initiative of F. A. Tsander and N. K. Fedorenkov, who spoke to Osoaviakhim USSR on the creation of an "Interplanetary Society." N. K. Fedorenkov announced through the press late in 1930 and early in 1931 that all those interested in problems of interplanetary voyages were invited to joint together and wrote in a letter to Ya. I. Perel'man that "the group for the study of reaction motion" was organized on 18 August 1931. This date is mentioned in the article "The Rocket and its Development" (1935).

Finally, a third point of view is defended by those who consider the date of founding of GIRD to be the day of the beginning of practical work on reaction equipment, namely 18 November 1931, when F. A. Tsander, who at that time headed the study of reaction motion in Moscow, concluded a "socialist agreement for strengthening the defense of the USSR" with the Bureau of Air Technology of the Scientific Research Section of CS Osoaviakhim for planning and development of working drawings, manufacture and production of models of a reaction engine, including installation of this LRE on an aircraft.

We note that it is this date, 18 November 1931, which was selected by a group of veterans of rocket technology of the

Soviet National Union of Historians of Natural Science and Technology, Academy of Sciences USSR, to hold a creative meeting dedicated to the 40th anniversary of the organization of GIRD in Moscow. This disagreement in the determination of the precise date of organization of GIRD is explained by the fact that the group was created gradually, its organizational forms changed, were improved and strengthened with each new step. /126

In 1932, CS Osoaviakhim adopted a resolution calling for broad development of work in the area of aviation technology. In particular, the Tsander group was encourated throughout 1932 to complete work on the creation of a reaction engine for an aircraft. In June of 1932, the Praesidium of CS Osoaviakhim adopted a resolution calling for the organization of an experimental scientific research base (GIRD), which was given the task of planning, construction and testing of engines and rockets of various types.

Thus, the group, which worked up to June of 1932 by popular support, was converted to a scientific research and experimental-design organization with its own staff and base. Financing was both through Osoaviakhim and through the Administration for Military Inventions (UVI) of the People's Commissariat for the Navy.

In 1932, GIRD was given space for the creation of a scientific research production design base beneath No. 19 Sadavo-Spaskaya Street in Moscow.

By July of 1932, the basic trends in the activity of GIRD and its structure had been determined. An order of CS Osoaviakhim of 14 July 1932 names Sergey Pavlovich Korolev as the head of GIRD, beginning 1 May 1932.

The structure of GIRD which had developed by mid-1932 reflected the trends of its activity. Four interrelated trends of work are characteristic:

-- scientific research and experimental work on the application of reaction engines;

-- broad technical popularization of the application of reaction engines;

-- training of workers in rocket technology;

-- leadership and coordination of the activity of the GIRD created across the country[1], allowing the Moscow group to be called the central group (TsGIRD).[2]

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[1]By this time, some 100 groups had been formed for the study of reaction motion.

[2]The name TsGIRD is first encountered in official documents on 31 March 1932.

The Chief of GIRD, Sergey Pavlovich Korolev (1933 Photo)

The work of GIRD was headed by the Technical Council, chaired by the chief of GIRD, S. P. Korolev. /127

Sergey Pavlovich Korolev was born 30 December 1906 in Zhitomir, the son of a teacher. In 1930, he graduated from Moscow Higher Technical School imeni Bauman and at the same time from the Moscow Pilot's School. S. P. Korolev created a number of designs of gliders which flew successfully. After familiarizing himself with the works of K. E. Tsiolkovskiy, he was attracted by the possibility of using liquid-fueled rocket engines for aircraft, gliders and rockets. Together with F. A. Tsander and other specialists in the area of rocket technology, he took part in the organization of GIRD in CS Osoaviakhim USSR.

After meeting F. A. Tsander, Sergey Pavlovich saw that the scientific ideas of Fridrikh Arturovich agreed with his own ideas to a great extent. Knowing that F. A. Tsander, who had studied problems of astronautics for many years, had much more experience and knowledge in the area of rocket technology than he, Sergey Pavlovich considered it necessary to bring the engineering developments of F. A. Tsander to life as soon as possible. S. P. Korolev considered that in order for the ideas of reaction motion to be accepted, a reaction flight vehicle would have to be flown, and that this would require that the OR-2 rocket engine plan by constructed.

Understanding the need for rapid development of experimental work, S. P. Korolev attached great significance to the development of massive propaganda. He dreamed of creating a series of popular books on rocket and space equipment. He himself managed to give time to this literary work. For example, in 1934, Gosvoyenizdat Press printed 20,000 copies of S. P. Korolev's work "Rocket Flight in the Stratosphere," /128 in which the need and means for mastering the stratosphere were clearly shown, conditions of high altitude flight were studied and the peculiarities of aircraft with reation engines were described. This work presents a description of a number of LRE which had appeared up to the time, as well as certain elements of the theory of reaction flight, including analysis of the formulas for thrust, exhaust velocity and efficiency.

"From the shores of the universe, which our Earth has now become," Sergey Pavlovich said, "Soviet ships will repeatedly fly far into space, lifted by powerful rocket boosters. Each flight and return will be a holiday for the Soviet people, for all forward-thinking mankind -- a victory of intelligence and progress."

The outstanding organizational capabilities of Sergey Pavlovich, the brilliant mind of this great scientist, allowed him to solve a number of important problems of rocket construction. During the post war period, S. P. Korolev directed the work of the design, scientific research organizations and test firing ranges for many years.

In the history of the study and mastery of space, the name of S. P. Korolev is connected to epochal achievements. The scientific and technical ideas of Sergey Pavlovich have been broadly realized in practice. Many ballistic and geophysical rockets, booster rockets, manned spacecraft and automatic interplanetary spacecraft (AIS) and artificial Earth satellites were created under his leadership. Sergey Pavlovich Korolev directed the launching of the world's first artificial Earth satellite, created the space rocket systems used for the first manned flight in space, the first flights of automatic spacecraft to the moon, Venus, Mars and the landing of an AIS on the moon.

S. P. Korolev was made a Corresponding Member of the Academy of Sciences USSR in 1953, an Academician in 1958. Sergey Pavlovich Korolev, a CPSU member, is a twice Hero of Socialist Labor and a Lenin Prize laureate.

The name of Korolev, one of the founders of astronautics, has been given to the largest formation on the far side of the moon.

GIRD consisted of four planning-design teams, combined into section I, production shops and a test station (section IV), an administrative division (II) and the organizational and mass operations division (III). GIRD was subordinate to CS Osoaviakhim. Sections I, II and IV were located in the basement of No. 19 Sadovo-Spasskaya Street and were a secret enterprise; section III functioned as an open and somewhat independent organization in Osoaviakhim.

The first team was headed by F. A. Tsander. The team included L. K. Korneyev (who later became the team leader in March 1933), A. I. Polyarnyy, L. S. Dushkin, A. V. Salikov, S. S. Smirnov, V. V. Griyaznov, Ye. K. Moshkin, I. I. Khovanskiy, /130
N. M. Vever, L. I. Kolbasina and A. I. Podlipayev. This team

tested the OR-1, worked on the preparation of suspensions of metal and kerosene, experiments on the ignition of metallic fuel in air. A suspension of magnesium and kerosene was suggested for the engines designed by F. A. Tsander as fuel. The suspension was produced using ball mills, and also by means of an electric arc. The OR-2 engine was tested with liquid oxygen and gasoline, the LRE 02 aviation-type engine was planned and tested, burning liquid oxygen and ethyl alcohol as well as the LRE 10, designed for the GIRD-X rocket.

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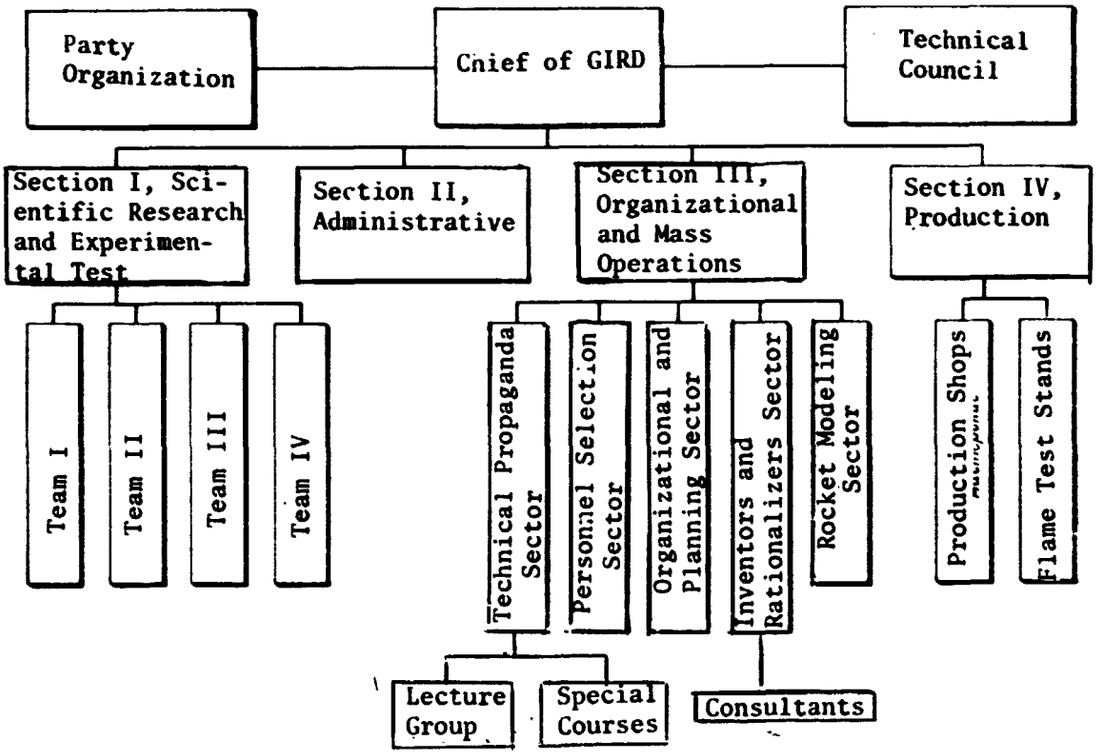

Organizational Plan of GIRD

The second team was headed by M. K. Tikhonravov. It included: V. A. Andreyev, V. N. Galkovskiy, Ya. A. Golyshev, N. I. Yefremov, V. S. Suyev, Z. I. Kruglova, O. K. Parovina, Ye. I. Snegirev, V. A. Fedulov, N. I. Shul'gina and F. A. Yakaytis.

Under the leadership and according to the plan of M. K. Tikhonravov, the second team developed the GIRD-09 rocket with the 09 hybrid-fuel engine. The second team developed the 07 rocket, flight tested in 1935. This team attempted to create an aviation engine with pump feed of liquid oxygen and gasoline. Other developments were also conducted.

Mikhail Klavdiyevich Tikhonravov was born 29 July 1900. He began his creative activity in 1923 when he was still a student at the Military Air Academy imeni Zhukovskiy. After graduating from the Academy in 1925, M. K. Tikhonravov was sent to work at the Aircraft Design Bureau of N. N. Polikarpov. In 1930, M. K. Tikhonravov was transferred to work at the Central Design Bureau imeni Menzhinskiy, where he used his work on aircraft motor equipment as a basis for his brochures "Aviation Tanks" (1934) and "Aviation Motor Supply and Lubrication Systems" (1936). In 1932, M. K. Tikhonravov, after meetings and discussions with S. P. Korolev, was transferred to GIRD. At RNII, M. K. Tikhonravov, together with a team from the Department of Wingless Rockets, began the development of a rocket to carry man into the stratosphere. Then M. K. Tikhonravov headed the Laboratory of Alcohol-Oxygen LRE. As a result of his scientific stucies on LRE, Tikhonravov published the articles "Use of Rockets for Investigation of the Stratosphere" (1936), "An Oxygen Rocket Engine " (1937), and "Principal Characteristics of a Rocket Engine" (1938) in the collections Raketnoye Tekhnika [Rocket Technology] and Raketnoye Dvizheniye [Rocket Motion].

In 1938, M. K. Tikhonravov began to study the stability of flight and reproducibility of trajectories of uncontrolled solid-fueled rocket weapons. The results of his studies were published in Raketnoye Tekhnika under the title "Study of Factors Influencing Firing Accuracy of Rocket Shells."

When he was leading the work on the investigation of /131
flight conditions of the artificial Earth satellite in 1950-1951, M. K. Tikhonravov was one of the authors of "Principles of the Theory of Flight and Elements of Planning of Artificial Earth Satellites." M. K. Tikhonravov also wrote many other works on problems of rocket technology.

The government of the USSR has evaluated the works of Mikhail Klavdiyevich Tikhonravov highly, awarding him orders of the Soviet Union, and giving him the Lenin Prize and the rank of Hero of Socialist Labor.

In January 1970, Mikhail Klavdiyevich Tikhonravov was selected a Corresponding Member of the International Academy of Astronautics.

The third team, headed by Yu. A. Pobedonostsev, studied and developed air-reaction engines.

Yu. Alekseyevich Pobedonostsev was born in 1907 and became a Doctor of Technical Sciences and Professor. He participated in the organization of GIRD. In 1932 he was transferred to GIRD as a full-time worker, where he led the development of direct-flow air-breathing reaction engines using solid fuel. Working

Mikhail Klavdiyevich Tikhonravov (1971 Photo)

at RNII, he contributed to the creation of the Katyusha rocket launcher. In 1968, he was selected as a Corresponding Member of the International Academy of Astronautics.

The third team successfully flight tested models of direct flow air-breathing reaction engines (DARL). The first domestic supersonic wind tunnel, created with the participation of M. S. Kisenko, an engineer in the third team, allowed the production of an open air stream from 40 to 60 mm in diameter at a velocity of 480 to 900 m/sec; working at reduced pressures, the gas stream could be increased to 1100 m/sec. The axisymmetrical nozzles used to produce the supersonic stream were designed by a method suggested by Professor F. I. Frankel. /132

Winged rockets were developed by the fourth team, the first leader of which was S. P. Korolev. Designer B. I. Cheranovskiy developed a glider for the OR-2 engine, which S. P. Korolev flew, prepared for testing as a rocket plane, later called the GIRD RP-1. The rocket plan had wind span of 12.1 m Its weight without the LRE was 200 kg. However, difficulties arising in development of the OR-2 prevented the RP-1 from being flight tested with the engine.

GIRD had experimental shops equipped with machine tools and various specialized devices. The production process was headed by P. S. Aleksandrov, I. A. Vorob'yev and Ye. M. Matysik. Flame testing of engines and flight testing of rockets were performed at the range in Nakhabino.

One important area of the activity of GIRD was propaganda and popularization of reaction motion.

This area was headed by the third section of GIRD, the organization and mass operations section. For reasons of secrecy, section III was placed separately from the other sections of GIRD in an open territory.

The work of section III involved not only the GIRD members, but also people working with popular support, not included as a part of the GIRD staff.

The activity of GIRD in the area of scientific and technical propaganda corresponded to the resolutions of the communist

party on problems of mastery of technology. We have in mind here the resolution of the CC VKP(b), adopted in 1931-1932 and designed to encourage broad development of technical propaganda in which, in particular, the need for comprehensive encouragement of all types of initiatives advancing the development of domestic scientific and technology was emphasized.

Between 30 January and 4 February 1932, the 17th Conference of the party gave particular attention to the need for the development of extensive scientific and technical propaganda.

Courses organized by GIRD in 1932 on rocket technology and /133
the history of astronautics were particularly significant in the training of specialists in the new technology. The course on the theory of rocket engines was read by F. A. Tsander, the course on the dynamics of reaction apparatus by V. P. Vetchinkin, the course on the theory of air breathing reaction engines by B. S. Stechkin, the course on hydrodynamics and gas dynamics by B. S. Zemskiy, while N. A. Zhuravchenko read the course of lectures on experimental aerodynamics.

In order to activate work in the field, the organizational and mass operations section of GIRD developed a program of courses for propagandists in 1932, designed for 40 hours. The training plans of the courses were sent out to peripheral organizations.

In April of 1932 there were six communists at GIRD, organized into a party group. The first party group organizer was L. K. Korneyev. In early 1933, an independent party organization was set up at GIRD. The first secretary of the party bureau was the Deputy Chief of the second team of GIRD, Nikolay Ivanovich Yefremov.

The communists of GIRD were the first combat detachment of the organization. The communists actively influenced the scientific and production life of all subdivisions of GIRD, and were leaders in the shock movement and in socialist competition. When difficulties arose in the work of any team, the party organization always mobilized the communists and gave help to lagging sections.

During the time of most intensive work, the communists gave personal examples, working day and night, as for example during the time of the first launching of the 09 and GIRD-X rockets.

2.5. Liquid-Fueled Rocket Engines and Rockets of GIRD

The primary results of the work of the first and second teams of GIRD were the 02 rocket for the RP-1 glider, the 10, 09 and 03 engines for the GIRD-X, GIRD-09, GIRD-07 and GIRD-05 rockets. Furthermore, experiments were performed with OR-1 and individual LRE units.

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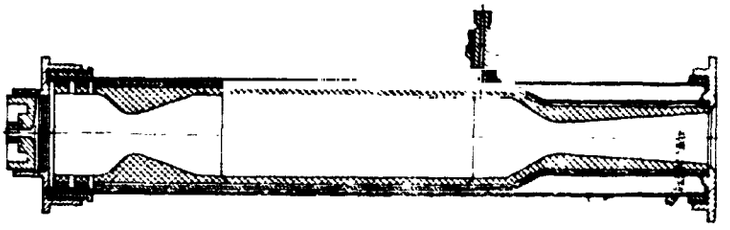

Cross Section of 02 Engine with Prechamber

The 02 Engine

Sergey Pavlovich Korolev (even before the organization of GIRD) attached great significance to the creation of a piloted flight vehicle with an LRE. This is indicated by his interest in the plans of F. A. Tsander, his great support of the work performed in the first team of GIRD on the OR-2 engine, the creation and personal leadership of the fourth team of GIRD, which developed the rocket plane flight vehicle, on which the OR-2 liquid fueled rocket engine was to be installed.

The 02 engine[1] was first tested in the OR-2 version, i.e., the form in which it was planned by F. A. Tsander.

After three tests (18, 21 and 26 March 1933), in order to improve the operating capacity of the 02 engine, further testing was performed with a fuel with lower heat content, consisting of liquid oxygen and 85% ethyl alcohol. Furthermore, the design of the liquid-carrying portion of the cooling system and of the combustion chamber itself was simplified; the cooling agent used was the liquid oxygen, the heating and partial evaporation of which in the cooling chamber had a favorable influence on processes within the chamber; the chamber was equipped with ceramic inserts, requiring studies on the selection of refractory heat insulating materials. Thus, the 02 engine differed significantly from the OR-2 designed by F. A. Tsander.

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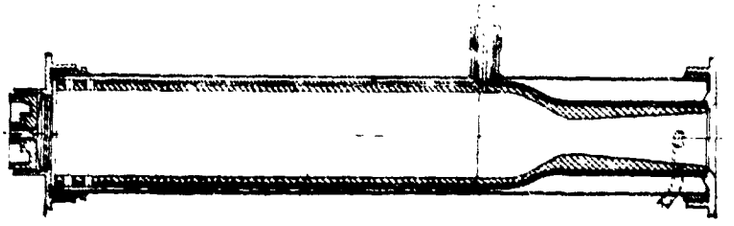
[1] In many documents this engine is called the "ORD-2."

During its development, the design of the 02 engine changed /135
from model to model. According to the special program of investigations, in July of 1933 a chamber was tested with a graphite insert, which burst during the 55th second of operation due to the presence of impurities in the graphite mass. In October, the chamber was tested with an insert made of carbon electrodes; the insert burned out during the 62nd second of operation. The insert or lining was a separate part (of graphite, aluminum oxide or magnesium oxide), placed tightly in the chamber and nozzle during assembly. In many cases, the refractory insulating material was applied in the form of a thick mass to the inner surfaces of the chamber and nozzle, then subjected to the required heat and mechanical treatments. In subsequent experiments, the graphite facing was covered by a protective refractory mass in order to avoid oxidation of the carbon.

By December of 1933 when the first team of GIRD had become a part of the RNII, it was finally established that the chamber should be lined with corundum, the nozzle with magnesium oxide, and on 20 December 1933 a chamber with this insulation operated 2 minutes 40 seconds without damage.

At GIRD, the development and testing of the 02 engine were conducted by A. I. Polyarnyy (Chief Designer), L. S. Dushkinym, L. K. Korneyev and other members of the first team. The development of heat insulating refractory coatings involved the participation of Ye. K. Moshkin. Final development of the engine was performed in the oxygen team of RNII, headed by M. K. Tikhonravov. Testing of the 6 main versions of the 02 engine on the stand of the third laboratory of RNII was conducted by L. S. Dushkin, A. I. Polyarnyy, B. V. Frolov and others.

The first version of the 02 engine was a cylindrical combustion chamber made of sheet copper 1.5 mm thick. The combustion chamber was lined on the inside with aluminum oxide, the nozzle -- with magnesium oxide. The shell of the chamber and the nozzle were made of low-carbon steel. The head of the engine carried a plate (called the jet plate) acting as a sprayer. The plate had 35 apertures 0.5 mm in diameter, through which the alcohol was sprayed. The oxygen, heated in the cooling /136
section and partially vaporized was fed into the combustion chamber through two tubes welded to the assembly ring in the area of the entry to the cooling section and apertures (windows) located in the cylindrical portion of the chamber wall near the head. Ignition was by spark plug, introduced to the combustion chamber before start-up through the nozzle.



Cross Section of Final Version of 02 Engine

The second version had a shaped nozzle, calculated by the method of Professor F. I. Frankel. Considering the complexity of manufacture of shaped nozzles and the multitude of problems not yet solved, GIRD did not continue to use this type of nozzle. Shaped nozzles became widely used only during the post war years.

The third version of the engine had a nozzle like the first version, but with a broader cone angle. The fourth and fifth versions were equipped with the nozzle of the third version and a prechamber. After a long series of tests performed in 1934-1935, the final version -- the 02-s engine -- was designed. This engine underwent testing in 1935.

The basic data of the final version of the 02-s engine are as follows. Length 570 mm, outside diameter 90 mm, diameter of critical nozzle cross section 26 mm, volume of combustion chamber 930 cm^3. The liquid oxygen consumption was 0.338 kg/sec, the consumption of 96% ethyl alcohol was 0.162 kg/sec. With a feed pressure of 20 atm, the pressure in the combustion chamber reached 11 atm. The engine developed a thrust of 100 kg and operated without damage up to 60 sec. The cylindrical portion of the combustion chamber was lined with a refractory heat insulating material based on aluminum oxide, the nozzle was lined with magnesium oxide.

Thus, an LRE was created as a result of work begun at GIRD and completed at RNII.

The 02-s engine was tested in 1936 on the 216 winged rocket. This rocket was launched from a catapult truck accelerated by solid fueled engines. Four tests were conducted; in two cases, the 216 rocket left the truck normally, climbing one time on an inclined, straight trajectory to an altitude of about 500 m. /137

The 10 Engine

The first team created the 10 engine for the GIRD-X rocket. It was designed to develop a thrust of 60-70 kg for a duration of 30 sec with a chamber pressure of 8-10 atm. The work on the engine was begun in January of 1933 under the direct leadership of F. A. Tsander.

The first version, developed by F. A. Tsander, was an engine which burned liquid oxygen and gasoline with the addition of metal, which was to be fed into the combustion chamber in powdered and melted form. In parallel with the planning of the engine, studies of the feeding and ignition of metal fuel were conducted, as a result of which it became clear that the preparation of metal fuel for combustion and use in the engine involved too great technical and operational difficulties. Therefore, the first version of the engine was not manufactured, and the second version was designed only for liquid oxygen and gasoline, without the addition of metal fuel.

The second version was an all-metal welded structure. The inner wall of the chamber was made of stainless steel, the outer wall (jacket) of ordinary structural steel. The engine was pear-shaped and featured external liquid cooling. It consisted of a mixing chamber with sprayers, a diffuser, and a central portion, i.e., the combustion chamber itself, and the nozzle. Liquid oxygen was fed to the lower portion of the nozzle through a collector into a cooling cavity 3 mm wide, then washed over the outside of the chamber wall and entered the chamber through jet-type sprayers. Gasoline was fed into the upper portion of the mixing chamber through jet-type sprayers, formed by drilling holes into the side surface of the chamber. The working mixture thus formed passed through a diffuser into the central portion of the chamber.

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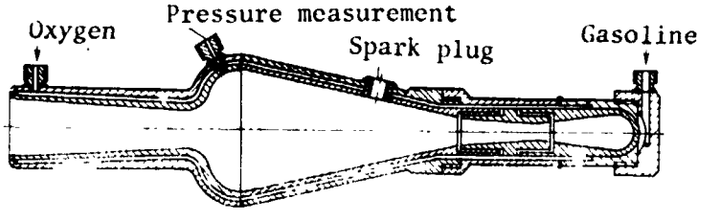


Second Version of the 10 Engine

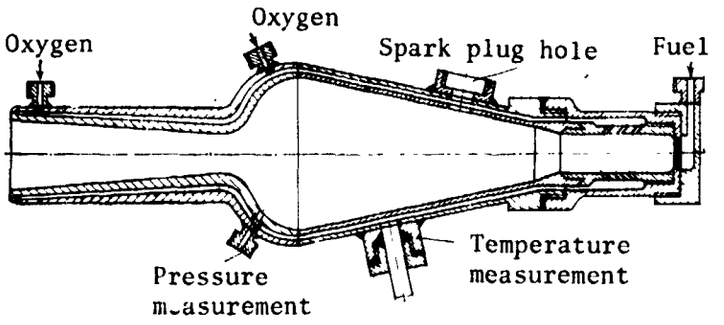
The testing of the 10 engine, begun in August of 1933, and the improvement of its design were performed by L. S. Dushkin, L. K. Korneyev, A. I. Polyarnyy, V. P. Avdonin, M. G. Vorob'yev

and others. During flame testing, changes were made in the design of the chamber. A chamber with a prechamber with a shaped contour was used; the prechamber was connected with the chamber by means of a diffusor. The engine was tested on liquid oxygen and gasoline. During flame tests, the excess pressure in the chamber varied little and did not exceed 2.5 atm.

The assigned time for fulfillment of the plan came to an end, and the engine had not yet been developed. Rupture of the combustion chamber required that further testing be performed using a fuel consisting of liquid oxygen and ethyl alcohol. The concentration of the alcohol (most frequently an 85% solution in water) was selected as a function of the assigned operating mode of the engine, and oxygen was used as before as the cooling fluid.

The third version of the 10 engine had a mixing chamber, i.e., a prechamber with a flat bottom, carrying the jet-type sprayers for alcohol feed. The fuel used was 78% ethyl alcohol. The oxygen sprayers were located on the cylindrical surface of the chamber, closer to the component mixing zone. The cooling of the central portion of the combustion chamber was intensified by additional input of liquid oxygen to the cooling cavity in the region where the combustion chamber was joined to the nozzle. During flame testing, the combustion chamber burst due to excessive thermal stresses.

The fourth version of the engine, made of SKh-8 steel, was tested on 2 October 1933 on the powder test stand at RNII. /139
The pressure in the chamber reached 8 atm, the thrust -- 75 kg. During the test, the peak of thrust was recorded when the operating mode was reached, then the thrust decreased during the 16th second. The engine was shut down after 21 seconds. An inspection revealed a crack in the inner wall of the central portion of the chamber.



Fourth Version of the 10 Engine

The next model of this engine was made of ENERZh-7 steel. It was tested together with the fuel feed system on a balance frame which carried the tanks, elements of the feed system and combustion chamber. The force developed by the engine was transmitted by this frame to the thrust-measuring device.

The basic data of the engine were as follows. Length 312 mm, outside diameter 92 mm, nozzle critical cross section diameter 24 mm, volume of combustion chamber 450 cm^3. The consumption of 85% ethyl alcohol was 0.280 kg/sec. With a pressure in the chamber of 10 atm, the thrust was 65-75 kg. The specific impulse, according to the data of three successive tests, was 162-175 sec.

Based on the results of the testing, the decision was made to install the engine in a rocket. The test report included the following:[1] "Since the design data have been exceeded and a thrust of 75 kg achieved, with a pressure in the combustion chamber of 10 am, operating time of 20 sec, and keeping in mind the slight, easily repaired damage to the chamber occurring during two tests, it is considered possible to launch the 10 rocket[2] burning liquid fuel into the air using the motor tested."

Work with the 10 engine was continued at RNII. Beginning in Febraury 1934, adjustment tests and further studies of this engine were conducted on the RNII test stand. The fuel was fed into the combustion chamber through jet-type sprayers. Two specimens were developed: an all-metal and a ceramic, i.e., with ceramic lining. The all-metal chamber differed little from the last GIRD chamber. /140

The other version of this engine had a nozzle with a refractory ceramic insert. The oxygen cooled only the central portion of the chamber and the mixing chamber. On 25 November 1934, during testing of the engine at RNII, it was considered possible to use the 10 motor with ceramic nozzle to launch rockets with powered flight times of 25-30 sec, since the thrust produced experimentally was 70 kg. The flame resistance of the nozzle made of ceramic was considered satisfactory, since no melting was observed after 25-30 sec operation of the engine.

The features of the 10 combustion chamber included the use of liquid oxygen and ethyl alcohol as fuel components, the

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[1] GIRD Archives, d. No. 3-050, p. 3.

[2] At GIRD, the rocket was called the 10. It was given the name GIRD-X later.

presence of prechambers, the pear shape of the combustion chamber, and the external liquid oxygen cooling.

The 10 liquid-fueled rocket engine was the first Soviet LRE tested by rocket flight.

The 09 Engine

The second team developed the 09 engine for the GIRD-09 rocket. After long search for the most expedient design, i.e., the most reliable design providing for the most rapid development, the team selected a hybrid fuel engine. This was facilitated by the suggestion that solidified (gelled) gasoline be used as fuel. This gel was produced by dissolving colophony in gasoline. Liquid oxygen was used as the oxidizer. The entire fuel reserve was placed in the inner cavity of the combustion chamber, while the liquid oxygen was poured into the fuel tank.

During planning of the GIRD-09 rocket, use of this plan allowed a reduction in rocket weight, simplified the design of the fuel feed system (only the oxidizer had to be fed into the chamber). True, the development of the mode of processes within the chamber was made more complex, and the evenness, stability and reproducibility of combustion of the fuel were reduced. /141

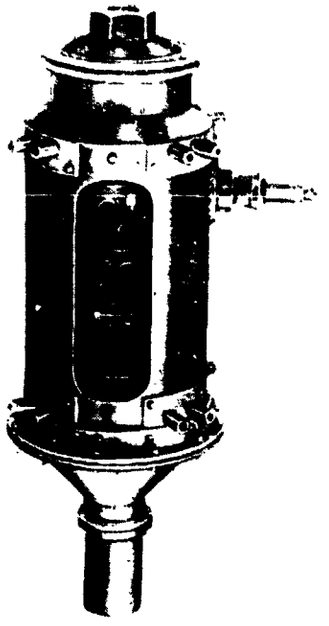
The chamber of the 09 rocket engine was made and tested in various versions differing in the design of individual elements.

The first model suitable for testing was completed on 31 December 1932, flame tests were begun in April of 1933.

The chamber of the rocket engine consisted of a sprayer disc, a cylindrical portion (combustion chamber) with a screen and the nozzle.

The sprayer disc was a disc with tiny apertures through which the liquid oxygen was sprayed into the combustion chamber.

The combustion chamber included a cylinder with apertures called the screen. The diameter of the cylinder was less than the diameter of the combustion chamber. The solidified gasoline was placed in the cavity between the screen and the chamber wall before start-up. The oxygen flowed through these holes in the screen to the gasoline and the combustion products flowed back through these holes into the central portion of the combustion chamber and to the nozzle.



Final Version of the 09 Engine

The chamber did not have external liquid cooling. The walls of the chamber were protected from burning by a layer of asbestos and by the fuel itself, which burned radially, i.e., in the direction from the screen toward the chamber wall. Thus, if the gasoline burned evenly, the combustion products could contact and heat the chamber wall only during the last instants of motor operation. /142

The nozzle was fastened to the cylindrical portion of the chamber; it also had no external liquid cooling.

The basic data on the engine are as follows. Thrust 25-33 kg, liquid oxygen feed pressure 13.5 atm, pressure in the combustion chamber 5-6 atm, length of chamber 320.5 mm, maximum diameter 145 mm, diameter of nozzle critical cross section 26 mm.

Flame tests of the engine were used to develop its individual units. In May of 1933, the team tested the combustion chamber for strength under static load and hydraulic shock conditions. In April and May of 1933, the oxygen valve, reduction valve and other units were tested.

In April of 1933, work was performed on the selection of the type of ignition. First, pyrotechnical ignition was tested. The igniter consisted of gun powder, wood charcoal and a (third) ballast component. Considering the insufficient reliability of the pyrotechnical ignition system, it was decided to use electric spark plugs powered by a magnito for ignition.

The engine was tested under the leadership of S. P. Korolev and M. K. Tikhonravov with the participation of N. I. Yefremov, V. S. Zuyev, Yu. A. Pobedonostsev, Z. I. Kruglovaya and other members of the group.

The chamber was first made of structural steel, then of copper. Seven tests performed beginning in July of 1933 showed that these chambers did not provide the required operating time, even when lined with asbestos. Chambers made of ENERZh steel were then tested. The final version of the chamber was made of brass.

The nozzle, first made of structural steel, was replaced with a copper nozzle, then with nozzles of ENERZh steel. These nozzles worked fairly well, although in some cases they were burned through in the region of the critical cross section.

Chambers with screens of various types were tested -- with ribs, to hold the solid gasoline in place and facilitate even burning, and without them; the material of the screen was varied (celluloid, aluminum, structural steel, chrome steel, etc.).

The chambers tested were equipped with heads of various types, differing in the direction of the jets, structural material and number of apertures, which was varied from 5 to 14. Each number of apertures produced a different thrust level. /143

Some tests resulted in explosions, as for example on 28 April 1933.

The pressure in the oxygen tank was developed by evaporation of a portion of the liquid oxygen in the tank due to heat exchange with the surrounding medium, and the design pressure was maintained in the tank by means of a safety valve.

Stable and reproducible pressure was not achieved immediately, resulting in repeated changes in the design of the oxygen valve, safety valve and other elements.

By mid-August 1933, the rocket engine, in the form in which it was installed in the rocket, passed final adjustment testing.

The 03 Engine

The 03 engine was designed for the GIRD-07 rocket developed in the second team by M. K. Tikhonravov, N. I. Yefremov, V. S. Zuyev and other workers of GIRD. It was constructed in 1933.

In this engine, spiral sprayers similar to the sprayers used in 1932 in the ORM-12 engine were used to inject the fuel (gasoline). The combustion chamber of the 03 engine was connected to the nozzle by a threaded joint. The combustion chamber did not have external liquid cooling. Testing of the engine began 17 October 1933. Beginning in February of 1934, ethyl alcohol was used as the fuel rather than gasoline.

The engine had the following design data: pressure in chamber 18-20 atm, thrust 80-85 kg, operating time 22-27 sec.

After a number of unsuccessful tests, work on the 03 engine was halted, and the 10 engine was installed on the GIRD-07 rocket.

One of the peculiarities of the operation of GIRD was the assignment of each LRE developed to a given rocket in order to power its flight. Therefore, in analyzing the activity of GIRD, we cannot limit ourselves to analysis of work performed with LRE on the test stand. GIRD set itself the primary task of achievement of rocket flight with LRE. It was therefore frequently called the rocket organization. /144

The GIRD-09 Rocket

The first Soviet experimental rocket, with the 09 hybrid-fuel engine, was created in the second team of GIRD under the leadership of M. K. Tikhonravov.

In August, 1933, the GIRD-09 rocket passed preliminary tests and attempts were made to launch it, unsuccessful for various technical reasons. After elimination of individual problems, on 17 August 1933, under the direct leadership of S. P. Korolev, the rocket was launched and the first hybrid fuel rocket in the world flew.

This date has entered the history of astronautics as the day of the launch of the first Soviet liquid-fueled rocket.

The basic data on the GIRD-09 rocket are[1]: length 2.4 m, diameter 0.18 m, launch weight 19 kg, including 5 kg of fuel, payload weight (parachute and several instruments) 6.2 kg. The 09 engine installed on the rocket developed a thrust on the order of 25-33 kg.

The main parts of the GIRD-09 rocket were made of aluminum alloys. The rocket consisted of a body, the lower portion of which carried four stabilizers. Inside the body was the oxygen tank, made of a pipe. The large annular clearance between the tank and the body acted as thermal insulation. Between the oxygen tank and the chamber of the rocket engine was a manually operated starting valve. The nose portion of the rocket carried the parachute and its ejector.

The launch of the rocket on 17 August 1933 was conducted as follows. After it was placed on its vertical guides, the rocket was filled with liquid oxygen. Heat exchange with the

[1]At GIRD, this rocket was called the 09. The name GIRD-09 was given the rocket significantly later.

surrounding medium caused a portion of the oxygen to vaporize, increasing the pressure in the tank. When the design pressure was reached, the oxygen start valve was opened and at the same time power was fed from the magnito to the spark plug; the fuel in the chamber ignited, and the motor came up to power. During this launch, the rocket left its guides and rose to an altitude of 400 m. /145

The entire flight, from launch to landing, lasted 18 sec. During a second launch in the fall of 1933, the engine exploded after the rocket reached a height of about 100 m.

In 1934, now in RNII, several GIRD-09 rockets were made, with slight changes in design, and a number of successful flights were conducted. The greatest altitude reached by the rocket was 1500 m.

The GIRD-X Rocket

The first experimental Soviet rocket with LRE was the GIRD-X rocket with the LRE 10, burning liquid oxygen and ethyl alcohol. The initial development of the rocket was performed by F. A. Tsander, the working plan, supplementary testing of units, assembly of the rocket, finishing of the entire complex of equipment and launching of the rocket were by the members of the first team of GIRD.

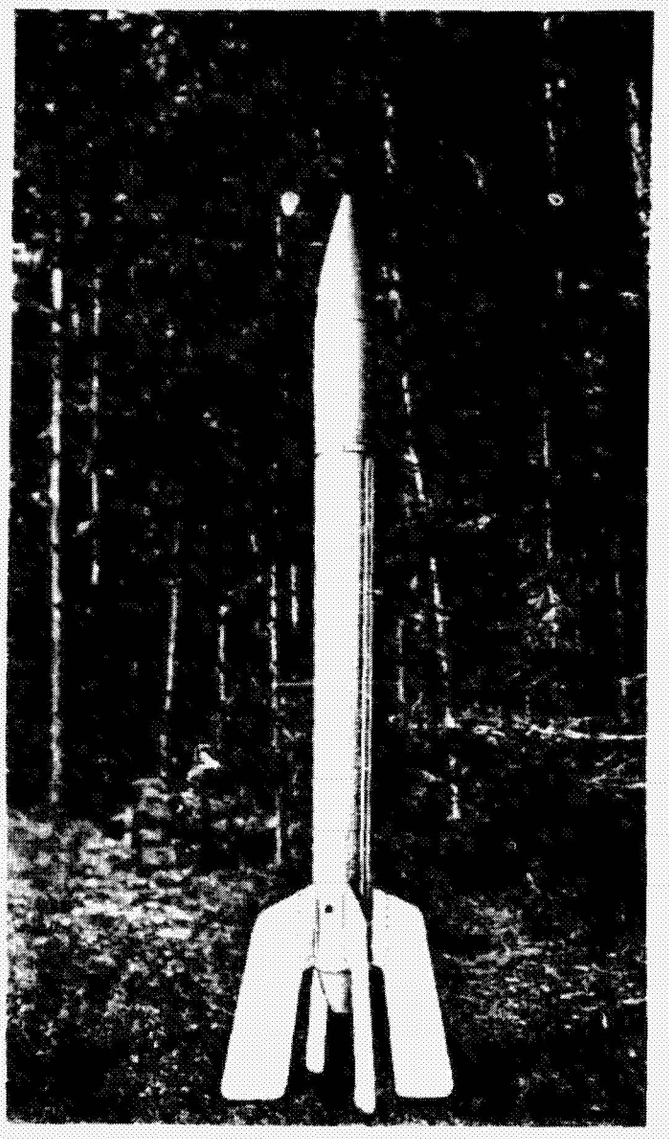
The principal plan of the rocket was developed by the members of the first team, based on materials of F. A. Tsander. Then a rough plan of the rocket was made up and ballistic calculations were performed -- the center of gravity, center of lateral effort, dimensions of tail fins and stability over the entire flight trajectory were calculated.

Using the methods of LRE design developed by F. A. Tsander, A. I. Polyarnyy, L. S. Dushkin and other workers calculated the basic version of a rocket engine combustion chamber in detail. Experimental data produced in the development of the versions of the 10 engine described above were used.

The launch weight of the rocket was 29.5 kg, 8.3 kg of which was fuel, 2 ig -- the nose portion.

The rocket consisted of five sections. In the first section, the nose portion of the rocket, was the parachute and its ejection device; in the second section was the oxygen tank and equipment; the central, third section, carried a cylinder with air compressed to 150 atm. Here also was the start-up equipment, including a pressure reducer, starting valves, etc. The fuel section contained a tank of alcohol. /147

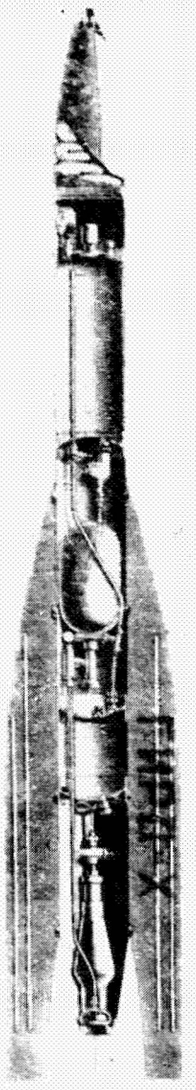
The bottom, motor section carried the engine and the start valve on the fuel feed line.



The 09 Rocket

The first launch of the rocket, under the direct leadership of S. P. Korolev, was held on 25 November 1933 and went as follows. After testing of all equipment, the rocket was placed on its guides and the pressure accumulator cylinder was charged. Then the tanks were filled with the fuel components: first the fuel, then the oxidizer. After checking the pressure, the start valves were opened and the magnito fed current to the electric spark plug. The rocket smoothly lifted off from the launch support and began to climb vertically with rapidly increasing speed. At an altitude of 75-80 m, due to damage to the motor mount, the rocket changed its flight direction sharply and fell to Earth at a distance of 150 m from the launch point. The engine, which fired for 12-13 sec, developed a thrust on the order of 65-70 kg in flight.

The launching of the GIRD-X rocket involved the participation of L. K. Korneyev, L. S. Dushkin, A. I. Polyarnyy, K. K. Fedorov, L. N. Kolbasina and other.



The GIRD-X, the First Domestic Rocket with LRE

The design of the GIRD-X rocket was further developed in later, improved Soviet rockets.

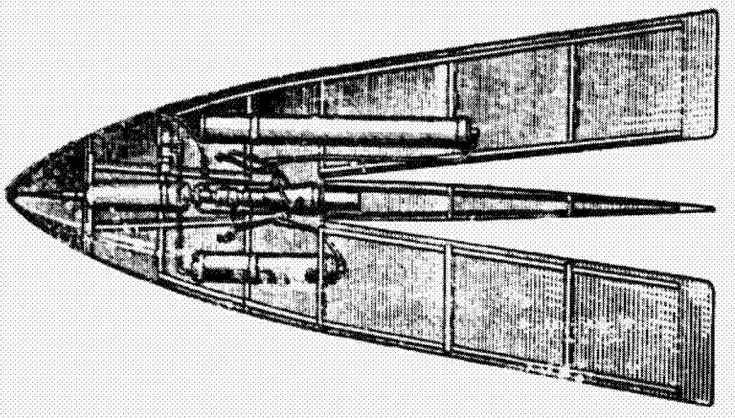
The GIRD-07 Rocket /148

This rocket was developed by the second team of GIRD in 1933. It had an unusual shape, a result of the search for improved aerodynamic characteristics, since the GIRD-07, like earlier rockets, was not planned to be equipped with a control system. The diagram of placement of the engine in the rocket and the design of the stabilizers were selected on the assumption that flight stability of the rocket would be increased by moving the point of application of the thrust vector closer to the nose portion and further from the center of lateral effort of the rocket.

In its final version, the rocket was driven by the LRE 10 developed in the first team of GIRD. Liquid oxygen and ethyl alcohol were carried in tubular tanks mounted one in each of the four stabilizers. The fuel components were fed to the combustion chamber under compressed air pressure.

The rocket was tested 17 November 1934 at RNII. M. K. Tikhonravov, V. S. Zuyev, Yu. A. Pobedonostsev, L. S. Dushkin took part in the test. Five to eight seconds after the command for ignition was given, sparks burst from the lower portion of the rocket. Immediately thereafter, one of the stabilizers caught fire. The burning continued 27 seconds, after which the engine was switched off. The rocket did not move /150 from its position and remained in the guides. Inspection after the test revealed that the combustion chamber and alcohol tank had burned through. The resport on the test of 17 November recommended further development of the engine and rocket. The 07 rocket was later tested in flight.

Many ideas and promising design solutions were embodied in the GIRD-09 and GIRD-X rockets; their flights of 17 August and 25 November 1933 laid the foundation for flight testing of liquid-fueled rockets in the USSR.



General View of the 07 Rocket

In Nakhabino, near Moscow, on the site where the GIRD-09 and GIRD-X rockets were launched, an obelisk has been placed, carrying the names of S. P. Korolev, F. A. Tsander and M. K. Tikhonravov.

Air Breathing Reaction Engines

The theory of air breathing reaction engines, developed by Boris Sergeyevich Stechkin, allowed practical work to be begun on the creation of air breathing reaction engines. The first experimental studies of direct-flow air breathing reaction engines were performed at GIRD, in the third team, led by Yu. A. Pobedonostsev. The theoretical calculations were followed by practical work -- experimental study of models of ARE and individual elements on the IU-1 test stand, built in March of 1933 for this purpose.

On 15 April 1933, the first ARE was started, and operated for 5 minutes. It was noted in the conclusions that the tests of the engine fully justified the theoretical assumptions. These tests served as the basis for experimental studies of ARE in the USSR.

As work on the testing of ARE models developed, the methods of study were also improved. Beginning in June of 1933, tests on the IU-1 included the measurement of the thrust developed by the engine being tested.

Since Yu. A. Pobedonostsev suggested that slowly burning solid fuels be used, after studying a large number of fuels, he selected white phosphorus and solid gasoline. On 12 July 1933

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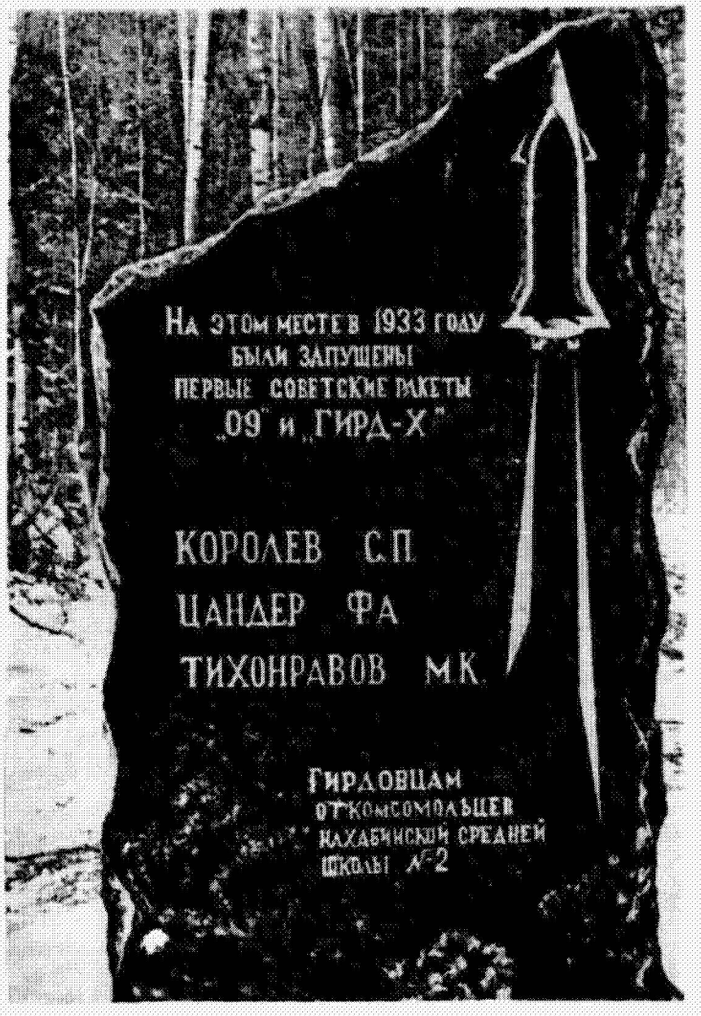

At the Launch Site of the First Domestic Liquid-Fueled Rocket [Inscription Reads: On this site in 1933, the first Soviet rockets, the "09" and "GIRD-X" were launched. Korolev, S. P., Tsander, F. A., Tikhonravov, M. K., to the GIRD workers from the Komsomol members of Nakhabinskaya Middle School, No. 2]

at a firing range near Moscow, a fully successful test of a combustion chamber burning phosphorus was conducted. During the tests of this same ARE with solid gasoline, ignition was /151
achieved by a chunk of phosphorus placed in the axial channel of the combustion chamber. In order to develop the most successful means of ignition of the fuel in the combustion chamber of ARE, a number of tests of powder ignition devices were conducted in July of 1933, including tests with a conical chamber burning ethylene.

To increase the effectiveness of ARE not only at supersonic, but also at subsonic velocities, a search was conducted to find plans in which the incoming air was not only compressed in a diffusor by the velocity head, but also by some other sort of additional device; a plan was drawn up for a pulse jet, in which the air stream was periodically admitted to the chamber by a valve moved by the pressure drop between the diffusor and chamber. An experimental combustion chamber was constructed at GIRD in June of 1933 to study the possibility of creating pulse jets.

The tests of pulse jets performed at GIRD in 1933 indicated the basic problems arising in the design development of engines of this type, and allowed the volume and difficulty of solution of these problems to be estimated. It was decided to direct all attention toward the study of ram jets, as the most promising type, but the study of pulse jets was reactivated at RNII in 1936-1939.

The successes of the first experimental studies allowed flight testing of ram jets to be undertaken. Yu. A. Pobedonostsev suggested that the engine to be tested be included in the body of an artillery shell, so that the jet could be tested at supersonic speeds, i.e., in the area where ram jets are most effective. The first series of flight tests in September of 1933 confirmed the calculation data. In February of 1934, now at RNII, a second series of tests was held and in 1935 a third series of jet flight tests was conducted. Six more versions of engines were planned for these tests, placed in the body of a 76 mm shell. Some versions included several groups, differing in the dimensions of the diffusor inlet cross section and the critical cross section of the nozzle and fuel reserve.

The ram jet engines designed by Yu. A. Pobedonostsev were /152
the first reaction engines which operated in the supersonic range. The experiments confirmed the primary theoretical conclusions of B. S. Stechkin on the efficiency of engines of this type and the need for further improvement of their design. The experience of later years showed that the scientific direction developed in the third team of GIRD was fruitful. In later years, designers concluded that future large booster rockets could use ARE as first stage engines.

Thus, GIRD demonstrated broad capabilities for practical realization of the leading ideas of Soviet rocket scientists in a short time: work on the creation of LRE (OR-2, 02) for piloted vehicles, rockets with LRE (GIRD-X), with hybrid fuel engine (GIRD-09), study of direct flow air breathing reaction engines. The development of reaction and rocket-space technology indicates the correctness of the scientific trends selected

at GIRD, the timeliness of the statement and solution of complex problems of the new area of technology by GIRD.

2.6. The Leningrad Group for the Study of Reaction Motion (LenGIRD)

An important role in the development of studies on reaction technology was played by the Leningrad Group for the Study of Reaction Motion (LenGIRD), organized 13 November 1931 on the suggestion of the well-known aviator P. F. Fedoseyenko[1] in the Leningrad oblast Soviet of Osoaviakhim. The initiative group, in addition to P. F. Fedoseyenko, included: Professor N. A. Rynin, Ya. I. Perel'man, Engineers V. V. Razumov, M. V. Gazhala, A. N. Shtern, Ye. Ye. Chertovskiy, I. N. Samarin and M. V. Machinskiy. B. S. Petropavlovskiy and V. A. Artem'yev, workers of GDL, were very helpful in the organization of the group and its work.

Professor Nikolay Alekseyevich Rynin (1877-1942) was a comprehensively trained engineer, a great scientist and an outstanding lecturer. During the initial period of his scientific activity, his primary attention was concentrated on determination of the aerodynamic loads acting on various structures. A significant portion of his activity was dedicated to aviation, problems of flight in the stratosphere and interplanetar voyages, which he considered to be a logical continuation and completion of aviation. His scientific, engineering and pedagogic activity were combined with great organizational work. In 1909, he participated in the creation of an aerodynamics laboratory at the Peterburg Nikolayevskiy Institute of Railroads; he organized the first aviation competitions and flights in Russia; he himself took part as a pilot in flights of aircraft, controlled aerostats, and flew in balloons. In 1920, with his participation, a Department of Air Voyages was organized at the Petrograd Institute of Railroad Engineers. The department was later converted to the Civil Aviation Institute, then to the Leningrad Military Air

Nikolay Alekseyevich Rynin

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[1] P. F. Fedoseyenko was the commander of the Osoaviakhim-1 stratostat, which set a worl altitude record in 1934.

engineering academy, now the Military Air Engineering Academy imeni A. F. Mozhayskiy.

N. A. Rynin was an interplanetary flight enthusiast, the organizer and chairman of the Section for Interplanetary Voyages, created in 1928, in the Leningrad Institute of Railroad Engineers, where he began work as a professor in 1921. In addition to his active work on LenGIRD, he developed problems of the theory of interplanetary voyages and was published. He carefully collected and published in nine books, between 1928 and 1932, ideas of flight in space, myths and legends handed down from ancient times, the dreams of novelists, the results of theoretical and experimental studies of domestic and foreign scientists, etc.

Even today, the books of N. A. Ryninare of significant interest to historians and those interested in rocket and space technology.

The name of Rynin has been given to a crater on the far side of the moon.

Yakov Isidorovich Perel'man

Yakov Isidorovich Perel'man (1882- /154
1942) was a Soviet scientist, a well-known popularizer of mathematics, physics, chemistry and astronautics. His books "Interesting Mathematics," "Interesting Astronomy" and others, in which Ya. I. Perel'man describes the many interesting technical problems involved in the development of various scientists are still in demand today.

He was capable of showing phenomena seemingly quite common and ordinary in a completely new and unexpected light.

In 1915, a remarkable book by Ya. I. Perel'man entitled "Interplanetary Voyages" was published. It went through 10 printings in 20 years. The book is written clearly, studying the methods of flight of man in space then discussed in the literature from a scientific standpoint. Ya. I. Perel'man showed convincingly that at the present stage of development of science and technology only the rocket could be considered a reliable means of carrying man into space.

Yakov Isidorovich wrote books on Konstantin Eduardovich Tsiolkovskiy, Galileo Galilei and Thomas A. Edison.

In 1928, Ya. I. Perel'man took part in the work of the Leningrad Section for Interplanetary Voyages, and beginning in 1931 he directed the work of the Scientific Propaganda Group of LenGIRD. Beginning in 1934, after LenGIRD was converted to the Section for Reaction Motion of the Leningrad Bureau of Aviation Technology of the oblast Osoaviakhim Soviet, he continued his propagandistic work until the beginning of the Great Patriotic War. The name of Perel'man has been given to one of the craters on the far side of the moon.

On 13 November 1931, a general meeting of LenGIRD activists /155
was held in the District Red Army and Navy Hall. After the introductory words of Professor N. A. Rynin concerning the goals and tasks of the organization, V. V. Razumov presented a report on his plan for a high altitude rocket and the immediate possibilities for interplanetary flight. The meeting was ended by the election of officers of LenGIRD, which included V. V. Razumov (President), Ya. I. Perel'man (Vice President), N. A. Rynin and Engineer M. V. Gazhala. Later, M. V. Machinskiy was selected as Chairman of the Technical Council of the organization.

Vladimir Vasil'yevich Razumov

Vladimir Vasil'yevich Razumov was born on 15 June 1890 in Peterburg. After graduating from the Marine Engineers School in Kronshtadt, he worked at the Admiralty Ship Repair Plant until 1931; he was a scientific consultant for the Leningrad Division of Dirigible Construction and in 1933 headed a design bureau for the construction of an all-metal Tsiolkovskiy dirigible. V. V. Razumov headed the planning and design group of LenGIRD; under his leadership, eight rocket plans were developed in 1932-1933.

The next meeting of LenGIRD, involving about 40 persons, was held 21 November 1931. This meeting discussed practical measures related to /156
the development of work on the study of the primary problems of reaction motion. Five groups were created -- the Scientific Research Group (headed by M. V. Gazhala), the Planning-Design Group (headed by V. V. Razumov), the Scientific Propaganda Group (headed by Ya. I. Perel'man), the Laboratory Group (headed by I. N. Samarin) and the Rocket Port Group (headed by Ye. Ye. Chertovskiy). Each group included

five to six persons. The scientific secretary of the oblast Osoaviakhim Soviet, V. I. Shorin, took part actively in the formation of LenGIRD.

In 1932, courses on rocket technology organized by LenGIRD were conducted.

In 1932, three rockets were planned at LenGIRD with powder engines (a photographic, illumination and recording rocket), as well as a recording rocket with LRE, and in 1933, high altitude rockets with LRE were planned.

In order to develop rocket engines, two sections were organized in the Planning-Design Group of LenGIRD. One of these, headed by V. A. Artem'yev, created a number of solid-fueled rocket engines between 1932 and 1935, which were installed on all the experimental rockets of LenGIRD which were successfully flight tested. The second section, headed by A. N. Shtern, developed a rotary reaction LRE, the LRD-D-1, which burned liquid oxygen and gasoline. However, this engine was never completely constructed.

LenGIRD maintained communications with MosGIRD. MosGIRD had as many as 400 members.

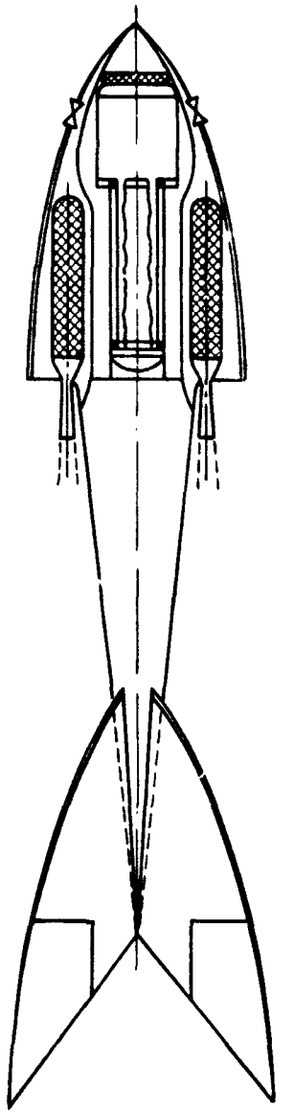
The Powder Rockets of LenGIRD

The photographic rocket, planned on the order of the Leningrad section of the Scientific Research Institute for Geodesy and Cartography, carried foru SRE designed by V. A. Artem'yev.

Calculated data: altitude of flight 10 km; total weight 26 kg, including 6 kg powder; total length 1.32 m; diameter of body 0.25 m; launch thrust 270 kg; engine operating time 4.33 sec; fuel -- smokeless trotyl pyroxylin powder.

The illuminating rocket was designed to supplement or replace searchlights, and also to blind enemy aircraft, as an air defense measure. The nose portion and stabilizers were made of aluminum, the combustion chamber and nozzle of the SRE -- of heat-resistant steel. /157

The calculated data of the illuminating rocket were: altitude of flight 5 km; total weight 18 kg, including 3 kg powder; total length 1.2 m; body diameter 0.15 m; launch thrust 81 kg; operating time of engine 4.35 sec; fuel -- smokeless trotyl pyroxylin powder.



The LenGIRD Recording Rocket

The plan for the rocket was completed in February of 1932. September of this same year, several experimental models were made at the Leningrad Mechanical Plant, which successfully passed flight testing at the Osoaviakhim range.

The recording rocket was designed to record data on the pressure and temperature of the atmosphere at altitudes of up to 10 km.

The rocket consisted of a nose portion with the required instruments, a body with stabilizers and rudders and four V. A. Artem'yev SRE.

The calculated data of the recording rocket are: total weight 30 kg, including 10 kg powder; total length 2.11 m; body diameter 0.23 m; launch thrust 148 kg; engine operating time 12.7 sec; fuel -- trotyl pyroxylin powder.

The plan for the recording rocket was produced in March of 1932 for the Leningrad Geographical Institute. Later, the design of the rocket was simplified, the dimensions were reduced and three versions were built: a high altitude rocket, an agitation rocket (with leaflets) and a shrapnel rocket. They were flight tested at the firing range in the Osoaviakhim camp. After summarizing the experience produced, the group of M. V. Gazhala planned, then manufactured in the mechanical shops another 20 rockets with similar SRE. The rockets, designed to reach an altitude of 1 km, were tested at the Aerological Institute in Slutska. /158

Liquid-Fueled Engines

For the recording rocket, LenGIRD developed a plan for two-chamber LRE, the LRD-D-1, which was to use liquid oxygen and gasoline. The nozzles of the two chambers had an inclined cross section, causing the rocket to rotate about its longitudinal axis; the centrifugal force caused the fuel components to enter the combustion chamber. The engine was called a rotating reaction engine. The basic elements of the LRD-D-1

rocket were made of steel. The walls of the combustion chamber and nozzle were to be cooled with the liquid oxygen, evaporating in the cooling spaces.

The calculated data of the rocket with LRE are: maximum altitude 5 km; launch thrust 200 kg with exhaust gas velocity 2000 m/sec; total weight 90 kg, including 17.8 kg oxygen, 4.89 kg gasoline; weight of engine 16.0 kg; total length 2.665 m; diameter of body 0.35 m.

The rocket was manufactured in 1932. Individual parts of the engine, combustion chamber and nozzle were exhibited during the first All-Union conference on the study of the stratosphere, held 31 March-6 April 1934 at Leningrad. Since the engine was never completely constructed and developed, the rocket was launched to determine its aerodynamic characteristics late in 1934 using the V. A. Artem'yev SRE.

In 1933, the group of V. V. Razumov began the development of the design of two recording rockets with design altitudes of 60 and 300 km with LRE burning liquid oxygen-gasoline fuel. The combustion chamber and nozzle were cooled with liquid oxygen, evaporated in the cooling space. The fuel component feed system was by compressed gas cylinder.

The calculated data for the rocket designed to reach an altitude of 60 km are: total weight 90 kg, including fuel 43.7 kg; total length 3.62 m; body diameter 0.35 m; launch thrust 1000 kg; engine operating time 28 sec.

The calculated data for the rocket designed to reach altitudes up to 300 km: total weight 150 kg, including 110 kg fuel; total length 5.9 m; body diameter 0.5 m; launch thrust 1571 kg; engine operating time 51 sec. /158

Since the necessary production base and funds were not available, this rocket was never manufactured.

During these years, a great deal of attention was given in LenGIRD to the selection of fuel for LRE, the search for the most favorable flight trajectories, the search for efficient rocket and engine element (combustion chamber, nozzle) forms, the gas dynamic studies of LRE, and the selection of materials for rockets and engines.

The workers of LenGIRD constantly conducted extensive explanatory work and gave consultation and practical aid in problems of reaction motion both to various teams which arose within the walls of military and civil educational institutions, and to individual enthusiasts.

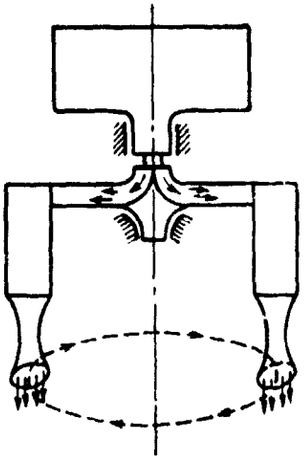


Diagram of Rotating Reaction Engine

In 1934, LenGIRD was converted to the section for reaction motion, which, under the leadership of M. V. Machinskiy, continued propaganda work, performed experiments on the effects of accelerations on animals and continued development and testing of LRE and rocket models right up to the beginning of the Great Patriotic War.

2.7. The Work of the Society

Problems of interplanetary voyages attracted the interest of many specialists. In addition to the state enterprises and groups for the study of reaction motion, individual persons, societies, sections, and clubs worked across the USSR, making no small contribution to the development of domestic rocket engine construction.

On 20 January 1924, at a session of the theoretical section /160
of the Moscow Society for Astronomy Enthusiasts, F. A. Tsander read a report "On the Design of an Interplanetary Ship and Flights to Other Planets," and suggested that a "Society for the Study of Interplanetary Voyages" (OIMS) be formed in the USSR.

In April of 1924, students at the Military Air Academy imeni N. Ye. Zhukovskiy created a section on interplanetary voyages in the Military Scientific Society of the Academy. The founders and most active participants in the section were V. P. Kaperskiy, M. G. Leyteyzen and M. A. Rezunov. The work of the section was supported by K. E. Tsiolkovskiy, F. A. Tsander and V. P. Vetchinkin.

On 30 May 1924, in the Great Auditorium of the Polytechnical Museum, a lecture was read by a great engineer and widely educated scientist, Mikhail Yakovlevich Lapirov-Skoblo, the subject of which was interplanetary voyages. The lecture showed how modern science and technology were capable of solving this problem. Then, members were signed up for the "Society for the Study of Interplanetary Voyages" (OIMS).

First, the society had some 200 members. They were located in the building of the Astronomical Observatory of the Moscow Division of Popular Education -- at 13 Bol'shaya Lubyanka (now F. E. Dzerzhinskiy Street). The society set very difficult tasks before itself -- the unification of all organizations, all scientists involved in problems of the study of interplanetary voyages, and the creation of a scientific research laboratory.

The first, organizational meeting of OIMS was held on 20 June 1924. The officers of the society were elected at this meeting -- a presidium consisting of: President-- the then well-known publicist and old Bolshevik G. M. Kramarov, Secretary -- M. G. Leyteyzen, members -- F. A. Tsander, V. P. Kaperskiy, M. A. Rezunov, V. I. Chernov, M. G. Serebrennikov. K. E. Tsiolkovskiy was elected as an honorary member. The society attracted the attention of talented scientists, engineers and designers to problems of astronautics and helped to popularize the ideas of rocket building and interplanetary voyages. K. E. Tsiolkovskiy, V. P. Vetchinkin, M. Ya. Lapirov-Skoblo and other famous scientists took part in the work of the society.

OIMS systematically held scientific-popular lectures. When it was reported that the USA planned to launch a shell designed /161
by Professor Goddard to the moon to celebrate Independence Day, July 4, OIMS held a debate on 1 October 1924 on the theme "Fligth to Other Worlds." Although the auditorium was large, it was not sufficient to contain all those who wanted to attend. Therefore, the debate was repeated twice -- on 4 and 5 October -- in the Great Auditorium of the First University Physics Institute. F. A. Tsander appeared on 4 October 1924 to report on a new ship which he had invented for space flight.

The society worked for comprehensive expansion of its propaganda activity. On 31 October and 2 November 1924, V. P. Vetchinkin read lectures in the Great Auditorium of the Polytechnical Museum on the possibility of interplanetary flight. Here also an informative report was read by V. I. Chernov on the construction of a rocket which he had designed. Lectures were read on interplanetary voyages at aviation plants, in the club of the Moscow Higher Technical School imeni N. E. Bauman, at the Astronomical Institute imeni Shternberg and elsewhere. Journeys by specialists were organized to read reports and lectures in other cities: Leningrad, Khar'kov, Saratov, Ryazan' and Tula.

OIMS existed but a single year, then broke up due to the fact that the tasks which the society had set before itself could not be performed with the funds available or the help provided by other organizations.

In June of 1925, Academician D. A. Grave spoke on the subject "A Request for Clubs to Study and Master Space." That same year, D. A. Grave, together with the great scientists Ye. O. Paton, B. I. Sreznevskiy, K. K. Seminskiy, V. I. Shaposhnikov and other enthusiasts, created a "Club for the Study of Space (the Cosmos)" in Kiev. The efforts of this club resulted in the opening of an exhibit dedicated to problems of the study of interplanetary space in the section of inventors of the Kiev Association of Engineers and Technicians on 19 June 1925.

In April-June of 1927, the world's first exhibit of models and plans for interplanetary apparatus and mechanisms was held at the Moscow Association of Inventors. This exhibit displayed interesting and unique materials on the work of Russian and foreign researchers.

The organizers of the exhibit were M. S. Belyayev, G. A. Polevoy, Z. G. Pyatetskiy, O. V. Kholshcheva. In late January 1927, persons interested in or working on problems of interplanetary voyages received invitations to take part in the organization of an exhibit. In a short time, many scientists and inventors sent in manuscripts, plans, drawings and models. The exhibit was held in Moscow, at No. 68 Tverskaya Street (now Gor'kiy Street) and was quite popular. The main portion of the exhibit consisted of the following sections: astronomical, aviation and air flight, science fiction, where the works of Jules Verve and H. G. Wells were presented, science-realistic, a significant portion of which was dedicated to the creativity of N. I. Kibal'chich, then an inventors section, in which the central position was occupied by materials describing the creativity of K. E. Tsiolkovskiy. The final, design section, presented plans for rockets of various types and their methods of flight. Here also were exhibited models of rockets and rocket apparatus designed by K. E. Tsiolkovskiy, F. A. Tsander, A. Ya. Fedorov, G. A. Polevoy (USSR), Eno-Pel'try (France), Goddard (USA), G. Oberth and Max Walier (Germany), F. A. Ulinskiy (Austria) and other. The exhibit was constructed so that it was all located around the Tsiolkovskiy section, the center of the theoretical division. /162

A significant role in the development of reaction motion was played by the scientific society and research orgniazations of Leningrad. For example, a scientific research section on interplanetary voyages was set up at the Leningrad Institute of Railroad Engineers on the initiative and under the leadership of N. A. Rynin. This section considered its main task the detailed development of problems related to "reaction flight."

The section held sessions quite regularly, discussing various problems of space flight. At one session, on 25 February 1929, Ya. I. Perel'man read a report, noting the first practical steps which needed to be taken by members of the section: namely the construction of rockets with engines burning liquid fuel (petroleum and its derivatives); experimental launchings, beginning with small powder rockets and gradually going over to more powerful rockets, in order to end this stage with the creation of a "stratosphere rocket," capable of reaching an altitude of 100 km or more. Professor N. A. Rynin took active part in the work of this section. /163

In connection with the organization of RNII in 1933, absorbing Moscow GIRD, the public activity of the latter

organization was continued by the reaction group of the Military Scientific Committee of CS Osoaviakhim, founded in January of 1934. The reaction group, soon reorganized as the reaction section, was subordinate to the Military Scientific Committee in the Osoaviakhim system.

On 6 January 1934, the first meeting of the reaction group was held, headed by I. A. Merkulov.

From 31 March through 6 April 1934, the reaction group, on the initiative of the Academy of Sciences USSR, held the first All-Union Conference on the Study of the Stratosphere in Leningrad. Primary attention was turned at this conference to problems of the creation of high altitude rockets.

In 1935, the reaction section held the first USSR conference on the application of rockets and rocket planes for the study of the stratosphere. In 1935-1937, exhibitions on rocket technology at the planetarium, Central Park of Culture and Rest imeni M. Gor'kiy and Central Hall of the Red Army were quite successful.

The lectors group, created in the reaction section read several hundreds of reports on reaction motion and interplanetary voyages during the time of its existence. The work of the section was publically supported, and involved the active participation of A. I. Polyarnyy, I. A. Merkulov, L. S. Dushkin, O. S. Oganesov, L. E. Bryukker, G. V. Overbukh, as well as professors B. S. Stechkin, V. P. Vetchinkin, F. I. Frankel', A. V. Kvasnikov, K. L. Bayev, B. M. Zemskiy and others.

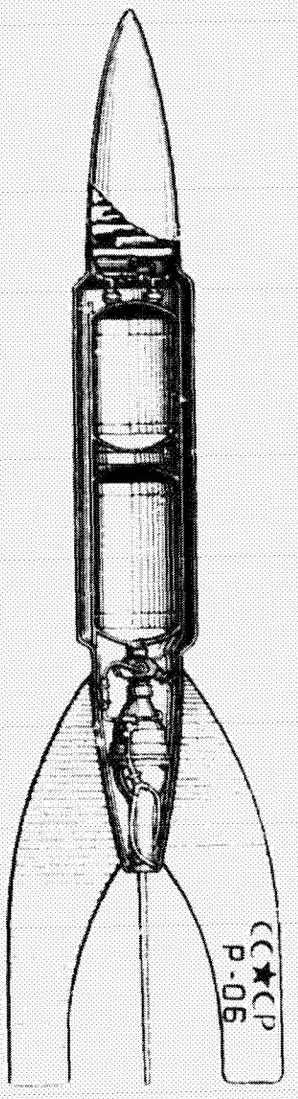
Between 1935 and 1938, the reaction section published three collections on "reaction motion," including the articles of domestic scientists -- K. E. Tsiolkovskiy, M. K. Tikhonravov, V. I. Dudakov, Ye. S. Shetinkov, V. S. Zuyev, I. A. Merkulov, F. D. Yakaytis, N. G. Chernyshev and others. A textbook on LRE was prepared. The USSR's first textbook on the design of liquid-fueled rocket engines was written by Ye. K. Moshkin and published in 1947. It was used in many higher educational institutions in the country for some 10 years. /164

One of the primary conditions resulting in the successful activity of the reaction section of CS Osoaviakhim was the scientific leadership of the leading scientists of RNII. Especially helpful were G. E. Langemak, M. K. Tikhonravov, V. P. Glushko, S. P. Korolev, Yu. A. Pobedonostsev and A. P. Vanichev.

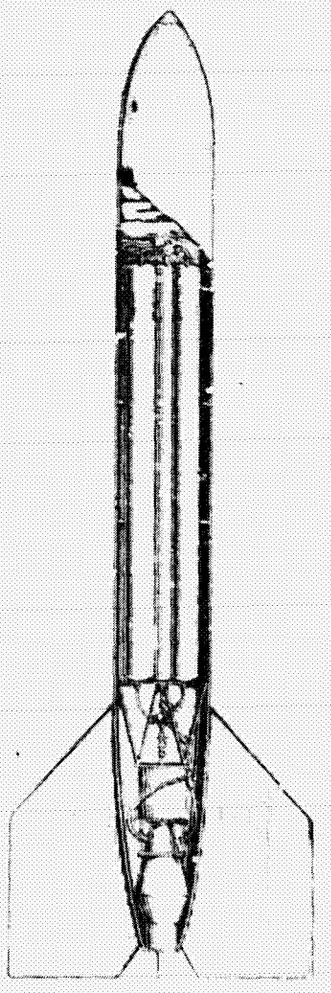
The reaction section also performed design development. For example, in the fall of 1934 under the leadership of A. I. Polyarnyy, a weather rocket with LRE was planned. The fuel components used were ethyl alcohol and liquid oxygen.

The first test launching of this rocket was conducted in 1935. The rocket was later modernized and began to be called the R-06. The first successful launch was conducted on 11 April 1937 near Moscow; six more launches were subsequently conducted.

The design data of this rocket are as follows: length with stabilizers 1.645 m; diameter 0.126 m; launch weight 9-10 kg; dry weight 6.5-7 kg; engine operating time 11 sec; engine thrust 40 kg; design vertical flight altitude 4.5 km; velocity upon leaving launch support -- 21 m/sec.



The R-06 Rocket



The "Aviavnito" Rocket

In this rocket, liquid oxygen was supplied from the tank to the combustion chamber under its vapor pressure; alcohol -- under compressed nitrogen pressure, with nitrogen occupying 65% of the volume of the alcohol tank. The LRE was made of stainless steel and cooled externally by its fuel. The fuel was electrically ignited. The nose portion of the rocket was opened when the proper altitude was reached and a parachute was ejected from the nose, returning the rocket smoothly to Earth. The tail section of the rocket carried four stabilizers.

In 1937, the reaction section created a second rocket with LRE, also burning ethyl alcohol and liquid oxygen, but water was sprayed into the combustion chamber to improve cooling. This naturally reduced the specific impulse and increased the weight of the rocket.

In 1938-1939, the reaction section planned the first Soviet two-stage rocket. It was made and tested under the leadership of I. A. Merkulov. The first stage had an engine /166
which burned a solid fuel -- smokeless powder. The second stage utilized an air breathing reaction engine (ARE). The launch weight of the rocket was 7.07 kg, the first stage weighing 3.51 kg, the second stage -- 3.56 kg.

The first successful launch was conducted 5 March 1939. During a flight on 1 September 1939, the engine of the first stage lifted the rocket to an altitude of 625 m, and achieved a flight velocity of 105 m/sec. After this, the first stage was separated by aerodynamic braking and the ARE of the second stage was ignited. It lifted the rocket to 1800 m; the rocket achieved a velocity of 224 m/sec. In 1939, these rockets were launched 16 times. All launches were conducted from a special vertical-type launch support unit with four guides.

During this time, there was yet another reaction section in Moscow, a part of an independent organization called the Stratosphere Committee of the All-Union Aviation Scientific Engineering and Technical Society "Aviavnito." This public organization was also involved in the study of the stratosphere and the development of the problem of reaction motion.

The reaction section of Aviavnito was involved in scientific and technical propaganda and the development of a rocket, transferred there from RNII, called the 05 rocket until 1935[1]. At first, the rocket carried the ORM-50 engine designed by GDL, and utilized nitric acid and kerosene as fuel. In the reaction section, the 05 was renamed the Aviavnito rocket, and a type 12K oxygen engine was installed.

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[1]Planning of the 05 rocket was begun in the second team of GIRD under the leadership of M. K. Tikhonravov.

The Aviavnito rocket had a streamlined shape, the nose por- carried a parachute and pyrotechnical device, while the tail portion carried the engine and equipment. The middle portion of the rocket carried four tanks made of duralium tubes: two tanks for ethyl alcohol and two for liquid oxygen.

The design data of the rocket are as follows: length 3.2 m, maximum diameter 0.3 m; launch weight 97 kg; dry weight 64.8 kg; fuel weight 32.6 kg (ethyl alcohol 13.4 kg, liquid oxygen 19.2 kg); engine thrust 300 kg; engine operating time 21 sec; flying altitude 10 km.

The walls of the engine were protected from overheating by /167
a ceramic lining, consisting of a mixture of magnesium oxide and aluminum oxide. The fuel was ignited by an electric spark plug.

The first launch was conducted 6 April 1937, the second -- on 15 August 1937. During the second launch, the rocket climbed smoothly upward, after which it lost stability and began to descent rapidly with the engine operating. The rocket utilized parts and assemblies from earlier rockets. A launch support 48 m high was constructed to launch the rocket.

The reaction section of Aviavnito planned two more liquid-fueled rockets. One at a maximum design flying altitude of 40 km, the other -- 65 km. Subsequently, work was continued only on the second plan, but the rocket was never built due to the lack of sufficient funds.

Interplanetary and reaction sections and groups were developed in many higher educational institutions and other organizations.

For example, in 1930 a student aviation builders club met at the Polytechnical Institute imeni M. I. Kalinin.

In 1938 a reaction section was organized at the Moscow Institute for Mechanization and Electrification of Socialist Agriculture (MIMESSKh), involving some 50 students in the senior classes. One result of the work of this section was a plan for a motor vehicle with an LRE.

The beginning of the Great Patriotic War hindered the continuation of experimental work. After the war, an engine was constructed and utilized in certain higher educational institutions for a number of years for the performance of scientific research and laboratory work.

The society was very effective in its work of scientific and technical propaganda, publication of scientific literature and training of engineering and technical workers in the area of rocket technology.

The work of the society on the study and popularization of rockets and space equipment was continued after the war. Lectors of "Znaniye" Society popularized the achievements of the Soviet Union in the area of the mastery of space, describing the design of rocket complexes. Clubs studying rocket technology and problems of space flight met at industrial enterprises. Rocket modeling became very popular among our youth. /169

A group of GIRD workers at the Sixth Readings: (Left to right) V. I. Aleksandrova, V. N. Galkovskiy, M. K. Tikhonravov, Ye. M. Matysik, O. K. Parovina, Yu. A. Pobedonostsev, Ye. K. Moshkin and I. A. Merkulov

In 1964, on the initiative of former members of Moscow GIRD, a GIRD workers group was created. For five years, the group worked fruitfully on the popularization of rocket technology, facilitating the organization and development of museums and exhibits, and worked on the collection and systematization of archive documents.

Based on this group, in 1970 the Group of Veterans of Rocket Technology of the USSR was created, including, in addition to the GIRD workers, the workers at many other Soviet organizations. Young specialists also took active part in the work of the group.

Memorial Symbol in Honor of 40th Anniversary of the Group for Study of Reaction Motion

The chairman of the group is Yu. A. Pobedonostsev. At a general meeting of the veterans, honored members of the bureau of the group were elected: outstanding Soviet scientists in the area of rockets and space technology. The following sections are included in the group: organizational, editing-publishing, propaganda and agitation, youth work and cooperation with museums and exhibits.

On 18 November 1971, the group of veterans held a Creative Jubilee Meeting dedicated to the 40th anniversary of the organization of GIRD in the USSR. At the meeting, reports were read by Yu. A. Pobedonostsev, B. V. Raushenbakh, I. A. Merkulov, Ye. K. Moshkin, B. M. Matysik and others.

Without doubt, the organization of this Institute became possible only due to the conditions created by the struggle of the Soviet working class under the leadership of the Communist Party.
I. T. Kleymenov

Chapter 3. The Reaction Scientific Research Institute (RNII) /170

3.1. Creation of the Institute

In 1931, the administration of GDL, and beginning in 1932 the leaders of Moscow GIRD and Leningrad GIRD repeatedly put forth the suggestion that the world's first State Scientific Research Institute for Rocket and Space Technology be created. The leading specialists in the area of rocket technology knew clearly that successes on a statewide scale could be achieved only by concentration of the forces of scientists in a large scientific research and experimental-design organization.

This suggestion was supported by the Deputy Commissar for Miliary and Naval Affairs, M. N. Tukhachevskiy, and an order of the Revolutionary Military Council of the USSR of 21 September 1933 called for the organization of the Reaction Scientific Research Institute (RNII) as a part of the People's Commissariat for Military and Naval Affairs. The new institute was based on GDL and Moscow GIRD.

A resolution of the Council for Labor and Defense of the USSR No. 4 dated 31 October 1933 transferred RNII to the People's Commissariat for Heavy Industry, and as of 4 April 1934 it was directly subordinated to the Scientific Research Section of this Commissariat. The Chief of RNII was Ivan Terent'yevich Kleymenov, his deputy was S. P. Korolev until January of 1934, after which Georgiy Erikhovich Langemak took over.

Ivan Terent'yevich Kleymenov (1989-1938) was one of the organizers and leaders of work on rocket technology in the USSR. In 1932-1933, he was the Chief of the Gas Dynamics Laboratory, in 1933-1937 -- Chief of RNII. His name has been given to a /171 crater on the far side of the moon.

Georgiy Erikhovich Langemak (1898-1938) was a Soviet artillery engineer, the designer of rocket weapons burning smokeless powder. He was one of the principal leaders of the development of rocket weapons at GDL and RNII, including those later used in the Katyusha rocket launcher. In 1934-1937, he served as Deputy Director and Chief Engineer of RNII.

The name of Langemak has been given to a crater on the far side of the moon.

The Chief of RNII, Ivan Terent'yevich Kleymenov

During the time of existence of this institute, its structure and the names of its subdivisions were changed repeatedly. During the initial period, the institute consisted of four sections, each section consisting of sectors, the sectors being divided into teams. Later, the institute was divided into groups. Furthermore, the institute included experimental production facilities, laboratories and service subdivisions.

The first section of the institute studied powder-fueled rockets and launch installations for them, i.e., combat devices. The second section worked on LRE: the nitric-acid team developed rocket engines utilizing nonvolatile oxidizers and kerosene; the oxygen team developed rocket engines burning liquid oxygen and ethyl alcohol.

The third and fourth sections developed winged rockets, air breathing reaction engines and other devices. /172

Georgiy Erikhovich Langemak

As the institute was organized, its staff included almost all the workers of GIRD and many of the workers of GDL, who were transferred from Leningrad. During its first months of existence, the institute hired new specialists as well.

From the very beginning of its activity, RNII established close cooperation with the founder of astronautics, K. E. Tsiolkovskiy. The workers of the institute visited Konstantin Eduardovich repeatedly, maintained correspondence with him, utilized his consultation and sent work to him for review.

On 23 February 1934, at a general meeting of the workers of RNII dedicated to the 15th anniversary of the Red Army, K. E. Tsiolkovskiy was elected as an honorary member of the Technical Council of the Institute.

Recognizing the services of K. E. Tsiolkovskiy, the Technical Council of RNII utilized the name "Tsiolkovskiy formula" for the

basic equation for the flight velocity of a rocket and "Tsiolkovskiy number" for the ratio of the mass of fuel reserve to the final mass of a rocket, suggesting that this ratio be represented by the letter "Ts."

3.2. The Activity of the Institute

The institute developed scientific research and experimental design work on solid-fueled rocket engines, LRE and flight vehicles, most of which had been begun at GDL and GIRD. /173

Powder Rocket Weapons

Powder rockets of various types and launch installations were developed at RNII under the leadership of G. E. Langemak by subdivisions headed by L. E. Shvarts, K. K. Glukharev, I. I. Gvay, V. I. Aleksandrov and others. During the initial period of existence of RNII, the workers of the institute were aided in the solution of many theoretical problems by scientists from the Artillery Academy such as D. A. Venttsel', M. Ye. Serebryakov, I. P. Grave and others, who took part earlier in the work of GDL.

The search for the most effective and economically favorable types of solid fuel (powder) for various models of reaction weapons was conducted in the powder shop, which was first located in Leningrad, but was transferred to Moscow in the first quarter of 1936.

Problems of the theory of interior and exterior ballistics of powder rockets were also studied in the late 1930's by Yu. A. Pobedonostsev, M. K. Tikhonravov, M. S. Kisenko, V. G. Bessonov and others.

By 1934, work had been widely developed on the creation of solid-fuel rockets of various sizes both for field artillery and for anti-aircraft purposes.

Solid-fueled rockets differ from rockets with LRE in their simplicity of design, high reliability, safety for the users and convenience of operation. Furthermore, the level of technology achieved in the 1930's was quite sufficient to support rapid development of mass production of solid-fueled rockets.

In July of 1937, the RS-82 air-air and air-ground reaction devices were fired. The military tests of the RS-82 were completed in November-December 1937 with group firing against surface targets on a training firing range from I-15 aircraft.

Late in 1937, the RS-82 was adopted for armament of the I-15 fighter. The airborne launchers were developed by A. P. Pavlenko

and N. G. Belov. Improved launchers were later developed by I. I. Gvay, A. S. Popov and others. In July of 1938, military tests of the RS-132 missiles, to be installed on bombers, were conducted. The tests were successful, and the RS-132 was also put in military use. /174

Air-to-air powder-fueled missiles were used in combat for the first time on 20 August 1939 by Soviet troops fighting the Japanese militarists in the region of the Khalkhyn-Gol River, when 5 I-153 fighters ("Chayka"), each armed with eight missiles, attacked a larger detachment of Japanese fighters.

The five first Soviet missile planes were led by test pilot Captain N. I. Zvonarev. This group, on five missions, shot down 10 fighters, 2 heavy bombers and 1 light bomber, without losing a single aircraft.

In 1938, RNII began working on a surface launcher for the RS-132 missile. The first models, with a capacity of 24 missiles, were mounted across the chassis of a truck. In the summer of 1939, considering the experience accumulated, a 16-missile launcher with guides directed along the chassis of a three-axle truck, was created. By late 1940, RNII had constructed six such installations. The missiles were fired, after jacking up the vehicle, in the forward direction, and the launcher was loaded from the rear. These devices, developed by engineers I. I. Gvay, V. N. Galkovskiy, A. P. Pavlenko, A. S. Popov and others, were prototypes of the BM-13-16 or Katyusha launchers.

A resolution of the State Defense Committee calling for series manufacture of rocket launchers was signed in June of 1941.

The BM-13-16 launcher was first used in combat on 14 July 1941 in the battery of Captain I. A. Flerov, a graduate of the Artillery Academy imeni F. E. Dzerzhinskiy. The German fascist troops occupying the railroad station at Orsh were quite surprised by a barrage of uncommon force at 15:30 hours. The entire station went up in flames, and powerful explosions went off one after another.

During the years of the Great Patriotic War, combat rocket launchers were used successfully in massive numbers, carried by wheeled and tracked vehicles as well as combat aircraft.

The rocket artillery fully confirmed its high combat qualities -- mobility and maneuverability, the capability for sudden concentration of fire at high densities over large areas with a rapid rate of fire.

Liquid-Fueled Rocket Engines

As we have noted, the second section of the institute worked /175
on the study and development of LRE.

The nitric acid team, headed by V. P. Glushko, continued the study and development of LRE begun at GDL, using nonvolatile nitrogen-containing compounds, primarily nitric acid with oxides of nitrogen, as well as tetranitromethane, as oxidizers.

Between 1934 and 1938, this team developed engine models from ORM-53 to ORM-71, plus the ORM-101 and ORM-102.

The primary task of this team was the creation of rocket engines and supplementary devices. Considerable attention was also given to problems related to the use of promising materials such as stainless, heat resistant, aluminum and other materials. New methods of welding and soldering were introduced, and experiments were conducted on increasing service life by chrome plating of worn surfaces. Since the engines were designed for both manned and unmanned flight vehicles, one important task performed by the team was reduction of the period required to reach nominal operation and automation of the launch.

The ORM-53 through ORM-63 engines were planned in 1934 and developed in 1935, followed by the ORM-64 and ORM-65.

The ORM-65 engine successfully passed adjustment and official testing in 1936, followed by surface testing on the RP-318 rocket plane and the 212 winged rocket in 1937-1938.

In 1939, the ORM-65 engine passed flying tests on the 212 winged rocket quite successfully and was highly evaluated.

After processing of a great deal of experimental data and conducting a series of scientific research operations in 1936-1938, the team developed the ORM-66, ORM-67, ORM-68, ORM-69 and ORM-70 engines with higher characteristics.

Furthermore, the team created various systems for LRE: turbine pump units, gas generators, automatic control elements, etc. In 1935-1936, for example, the first domestic gas generator, the GG-1, designed for production of the working fluid for the TNA turbine, was developed under V. P. Glushko. This gas generator passed official interdepartmental tests /176
successfully in 1937.

In 1939, V. P. Glushko was made the leader of an independent subdivision of the Aviation Motor Plant, separated from RNII. Therefore, the work of V. P. Glushko at RNII ended in 1938.

By 1939, after further testing, the RDA-1-150[1] liquid-fueled rocket engine for the RP-318-1 engine was planned on the basis of the ORM-65 engine, under the leadership of L. S. Dushkin.

However, the RDA-1-150 engine, due to its low thrust, was found to be unsuitable for unaided takeoff of an aircraft. Therefore, a more powerful nitric acid engine, the RDA-300, was planned and manufactured in the first half of 1939. During this same year of 1939, the RDK-1-150, burning alcohol and oxygen, was created.

The oxygen team, headed by M. K. Tikhonravov, developed engines burning liquid oxygen and an aqueous solution of ethyl alcohol. Means were sought to assure the most complete possible combustion of the fuel and increase the thermal efficiency. The results of theoretical and experimental work indicated that this required an increase in combustion chamber pressure. Therefore, even though increasing the pressure complicated the cooling problem, new engines were designed for combustion chamber pressures of around 15 atm, in place of the 5-8 atm used earlier.

Several versions of the 12K engine were first tested; in 1936, the oxygen team began development of the 205, 206, 207 and 208 engines, designed, like the 12K, for installation in rockets. The technical assignment for planning of the engines noted the need to eliminate the shortcomings of alcohol-oxygen engines developed earlier. It was also required to increase the reliability and reproducibility of test results and the specific impulse.

In early 1934, the group of L. K. Korneyev, working on the development of GIRD engines in order to increase the reliability and reproducibility of test results, was separated from RNII. Some of its workers later took part in the work of Design Bureau No. 7 (KB-7), organized as a part of the Main Artillery Administration of the Red Army and headed by L. K. Korneyev.

Air-Breathing Reaction Engines

In 1934-1935, RNII performed experimental work with direct flow air-breathing reaction engines (PVRD). Preliminary calculations and testing of PVRD models were performed at GIRD in 1932-1933. The experiments performed at RNII confirmed that PVRD, based on the theory of B. S. Stechkin, were suitable for use for flight at supersonic speeds. This work was performed under the

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[1]The symbol RDA-1-150 stands for "Rocket Engine, Nitric Acid, No. 1, Thrust 150 kg."

leadership of Yu. A. Pobedonostsev, with the participation of M. S. Kisenko, A. V. Salikov, I. A. Merkulov, U. S. Oganesov and A. B. Ryazankin.

PVRD Installation Designed by I. A. Merkulov on an Aircraft

In 1936-1939, the institute studied pulse jet engines. However, these engines were not further developed.

In 1937-1940, under the leadership of V. S. Zuyev and Ye. S. Shchetinkov, PVRD models were tested. Preliminary work on improvement and development of experimental methodology was performed using hydrogen fuel, after which an extensive PVRD testing program using devices burning gasoline was undertaken. Based on the experience accumulated, V. S. Zuyev designed a ram jet to be installed on an aircraft.

In 1942, flying tests of the jet engine designed by M. M. Bondaryuk were conducted on an LAG-3 aircraft. At this time, the Design Bureau was still not a part of the institute. Later, in 1946-1947, a ram jet engine for subsonic speeds was developed at RNII under the leadership of M. M. Bondaryuk. It was designed to be used as an accelerator by the LA-7 and LA-9 aircraft. In 1948-1950, a dual-loop aircraft PVRD was developed. /178

Late in 1944, an experimental turbojet engine, the S-18, was developed at RNII under the leadership of A. M. Lyul'k. Subsequently, the experience gained in working on this engine was used as the basis for the plan for the Soviet turbojet engine (TRD), which passes state testing in March of 1947. This work served as a basis for the development of air-breathing reaction engines in the USSR, which engines have been widely used by various aircraft since the war.

Flight Vehicles

RNII, under the leadership of S. P. Korolev, continued work on winged rockets -- air torpedos -- with both solid- and liquid-fueled engines, following the work undertaken on his initiative at GIRD. Preliminary calculations of the flight stability of winged rockets were performed by Ye. S. Shchetinkov and A. Markin under the leadership of A. V. Chesalov. The first rockets with LRE, called the 06 rockets, were flight tested in early 1934.

During the process of work on unmanned winged rockets, several flying versions of the 216 winged rocket with the 02 alcohol-oxygen LRE were created, then (1936) the improved 212 rocket, with the ORM-65 engine. An extensive program of stand testing of the various units of the engine and 212 and 301 rockets was undertaken, followed by flight testing of improved versions.

The 212 rocket, an all-metal device, consists of the following sections: nose section, carrying the payload and parachute; instrument section, for the stabilization and control system apparatus; fuel section, carrying the tanks; nitrogen section, carrying the pressure cylinder; and the engine section.

The fuel and oxidizer tanks, tubular in shape, were located within the wing. The fuel components were fed to the combustion chamber by compressed nitrogen pressure. The pressure reducers /179
for the nitrogen which was fed to the tanks from the pressure cylinder and the fuel valves were located at the plan center of the rocket.

The ORM-65 engine was carried in the tail portion of the rocket on a frame and covered by a fairing with a metal sleeve located above the nozzle exit plane to protect the rudders from the flame.

The device was launched from a catapult truck powered by a powder-fueled rocket, the combustion chamber of which contained packets of trotyl pyroxene powder (15 packets measuring 75 x 10 x 92 mm). The catapult truck rode on rails 150 m in length. The takeoff run required for the winged rocket during flight tests was 26 m.

The planned flight range of the winged rocket, with a launch weight of 210 kg and a fuel reserve of 30 kg, was 50 km.

The design of the RP-318 rocket plane was as follows: wooden, free flying monoplane, fuselage of oval cross-section with mid-section area 0.75 m^2; length 7.44 m, wing span 17 m, bearing surface of wing 7.85 m^2. Initial flying weight 700 kg. Launched from Earth as normal for gliders.

The steel fuel tanks located behind the metal back of the pilots seat carried 75 kg of fuel, sufficient for 100 sec continuous operation of the engine at a thrust of 150 kg. The capacity of the fuel tank, located directly behind the pilot's seat, was 20 ℓ, while the two oxidizer tanks, located at the center of gravity of the aircraft, had a capacity of 40 ℓ. In case of leakage, the oxygen tanks were contained in duralumin baths with a drain leading outside the aircraft. The oxidizer and fuel were fed to the engine under compressed air pressure, with the air carried in four tanks of 5 liter capacity, two in each wing. The air was fed to the fuel tanks through a pressure reducer. The engines were started by rotating a control lever, which mechanically opened the fuel valves located in the tail portion of the fuselage immediately before the engine. The fuel valves were opened when a signal lamp installed on the pilot's instrument panel lit up.

The RP-318 rocket plane designed by S. P. Korolev was tested with LRE about 40 times.

The engine was carried on a frame in the tail of the fuselage and mounted beneath a metal shield to protect the tail section from the flame. For this same purpose, the portion of the rudder closest to the engine was covered with a sheet of stainless steel 0.3 mm thick.

During the pre-war period of activity of RNII, almost all /180
of the creative workers and specialists in the area of rocket technology labored within its walls. The principles of the theory of rockets and engines were developed, operating models were created, which later saw practical application and development. RNII made a significant contribution to widely varied areas of rocket technology, thus providing a reliable foundation for Soviet rocket science.

3.3. Nitric Acid LRE

The ORM-53 - ORM-63 Engines

The nitric acid team worked on the creation of engines, utilizing the last LRE of the Gas Dynamics Laboratory, the ORM-52, as a prototype. The basic fuel components utilized in the engines developed, as before, were nitric acid and kerosene. Summarizing the experience of the work of GDL, the designers came to the conclusion that the reliability of engine starting in all nozzle positions would have to be improved, by using chemical and pyrotechnical ignition, that the fuel feed system would have to be developed to bring the engine up to full design thrust more rapidly, that the operating time of the engine would have to be increased, as well as the specific impulse, by improving

mixture formation. In order to decrease the weight of the engine, the feed pressure had to be reduced by improving the hydraulic characteristics while conserving the same pressure in the combustion chamber.

Taking these initial ideas, RNII developed a series of engines from ORM-53 through ORM-63 in 1934-1935.

In the ORM-53 engine, a number of design elements were improved over the ORM-52. The ORM-54 had external cooling of the nozzle by the oxidizer and higher spiral ribbing; the spray head and combustion chamber, as before, were protected from the effects of the high heat fluxes by an internal film (vapor curtain).

The ORM-57 8-sprayer high-thrust engine had a critical nozzle cross section diameter of 40 mm, an exit plane diameter of 100 mm, with a cone aperture angle of 20°. The aluminum nozzle insert consisted of 6 parts. This engine was planned but not manufactured. The first domestic two-chamber engine was the ORM-58, designed for a thrust of 600 kg. /181

Summarizing the experience gained in planning the engines from ORM-53 to ORM-62, the designers selected the best features and created the ORM-63 engine.

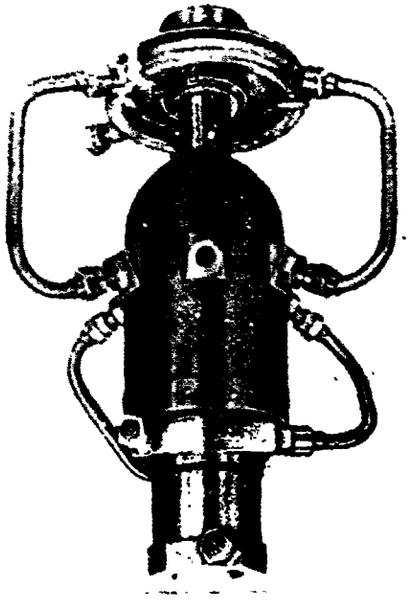
The ORM-63 was a fully cooled experimental engine developing a thrust of 300 kg. It underwent element-by-element technological development in production in order to assimilate a number of new technological operations: roller electric welding of the compensator, stamped from a sheet of stainless steel, to the nozzle and its jacket, butt electric welding at the critical cross section of the nozzle, high temperature hermetic soldering of various joints with high-temperature solder, etc. Particular attention was given to the quality of manufacture of parts, testing of subassemblies and the quality of assembly of the entire engine.

The combustion chamber of the ORM-63 utilized membrane-type hydraulically controlled spiral sprayers. The corrugated membranes were stamped of sheet stainless steel.

The ORM-64 - ORM-70 Engines

In early 1936, tactical and technical requirements were developed for an engine for use in the RP-318 rocket plane and the 212 remote controlled winged rocket. The engine was to develop a thrust of 150-160 kg, to operate continually for at least 75 sec per start and develop a specific impulse of at least 180 sec; its weight was limited to 10 kg. The variation in mean thrust from start to start of the engine during the period

of stable operation was not to exceed ±3 kg; the difference between values of mean thrust and maximum and minimum thrust during a single start of the engine during the period of stable operation should not exceed ±3 kg; the fuel feed pressure was not to be over 35 atm. The engine should operate normally in the horizontal and vertical position, and also with the inlet pressure choked from 35 to 12 atm by aoration of fuel flow rate. Particular attention was given to the assurance of high reliability of starting and operation. According to these requirements, the ORM-64 engine, as an experimental version, and the ORM-65 engine, as the basic operating version, were planned, constructed and tested in 1936. /182



The ORM-64 Engine

The ORM-64 was an experimental engine with a thrust of 150 kg, similar in design to the ORM-52 engine; it was a four-sprayer engine, combustion chamber volume 2.23 l, diameter of nozzle critical cross section 20 mm, exit plane diameter 40 mm, nozzle expansion angle 20°. At the center of the head was a device for ignition consisting of a sleeve carrying a current conductor (ES-Kh sparkplug), an electric cap and a 6-8 second metal-nitrate ignition cap, seated on a rod. The material of the chamber was carbon steel, the nozzle was made of EYa36 steel.

During test stand operation of the ORM-64 engine in the vertical (nozzle downward) and horizontal positions, the required technical and technical characteristics were achived, including the weight, which was 10 kg. With a pressure in the combustion chamber of 22.5 atm and a feed pressure of 27.5 atm, the engine developed a specific impulse of 216 sec. /183

The combustion chamber operated for a total time of 502 sec without defects; start-ups were shock-free, the engine operated at its design mode stably, without oscillations. With a continuous engine operating time reaching 120 sec, the cylindrical portion of the combustion chamber, due to the intensive process of fuel combustion, glowed bright yellow. This was due to the fact that the combustion chamber had not external cooling, the combustion chamber walls being cooled only by the spraying of the fuel components on its inner surface. In later designs of ORM, in order to assure higher reliability of the cylindrical portion of the combustion

chamber, it was cooled by a flow of nitric acid on the outside. Based on analysis of the results of these tests, the main version of the engine, the ORM-65, was developed, and successfully passed official stand tests in 1936, also in the vertical (nozzle downward) and horizontal positions. The ORM-65 engine was the most highly developed engine of its time.

The main data produced in the tests of 1936 were superior to the assigned tactical and technical requirements, except for weight, and were as follows.

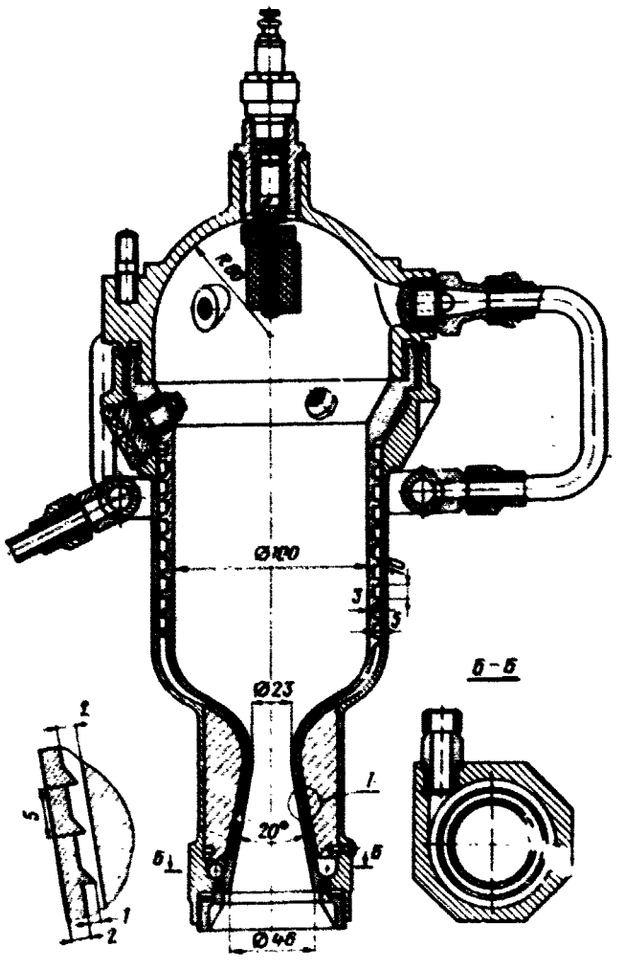
Thrust at ground level in maximum mode 175 kg, in nominal mode 155 kg, in minimal mode 50 kg; specific impulse in maximum mode 195 sec, in nominal mode, average mode for the entire time of stable operation, 215 sec; combustion chamber pressure in maximum mode 25 atm, in nominal mode 23 atm and in minimal mode 8 atm; fuel consumption in maximum mode 0.900 kg/sec, in nominal mode 0.738 kg/sec. Method of start-up manual on signal lamp or automatic.

The ORM-65 combustion chamber, with a volume of 2.01 ℓ, consisted of three steel main parts: the spray head, chamber nozzle and jacket, sealed with an asbestos liner. The chamber head, designed to prepare the fuel for combustion, with internal film cooling, had an operating surface temperature of 300-400° C. The combination chamber and nozzle consisted of the cylindrical portion of the combustion chamber, made in one piece with the nozzle. It was equipped with external flow cooling; in order to increase heat transfer, the chamber-nozzle had spiral ribbing in two places. The pressure drop through the cooling fluid line was 3.5 atm when operating in nominal mode.

The necessary jacket gap at the nozzle was provided by the installation of two shaped aluminum inserts. /186

The nozzle was equipped with a compensator -- a lead liner, held under pressure by a threaded ring. This compensator allowed thermal elongation of the chamber and nozzle relative to the cooler jacket (with the lead flowing into the circular gap between the jacket and chamber-nozzle), while maintaining the tightness of seal. After each test, the pressure ring had to be tightened up to restore the seal.

The fuel components were sprayed into the combustion chamber through centrifugal-type sprayers (three oxidizer sprayers and three fuel sprayers alternating at intervals of 60°). The oxidizer sprayers were installed in the head portion of the chamber at an angle of 60° to the axis and directed opposite to the nozzle. The fuel sprayers were installed in the head perpendicular to its axis.



Cross-Section of the ORM-65 Engine

The ignition device consisted basically of a current conducting plug, cartridge with an electric cap and pyrotechnical igniter (metal-nitrate) cap. /184

When the ignition circuit was closed, the wire in the electric cap burned out, igniting the charge of smokeless powder in the cartridge. The hot powder gasses, flying out through the channels in the cartridge, ignited the cap. The ignition cap, which burned from one end, was cylindrical in shape, 24 mm in diameter and 40 mm long with a central inner channel protected by a duralumin tube. The fuel components were fed to the chamber only after good ignition of the igniter cap.

This was achieved by connecting a low-resistance shunt, which passed through a hole drilled in the side of the cap, in the ignition circuit in parallel to the control lamp installed on the control panel or the automatic starting device. When the shunt burned through, the lamp lit fully, which was the signal to open the fuel valves for manual start or put the automatic start mechanism in operation. The distance of the shunt from the end of the cap was selected so that it would burn through in about 4 seconds, when the cap would be well ignited.

The ORM-65 engines were operated repeatedly. For example, ORM-65 No. 1 was started 49 times and operated 30.7 minutes on the ground, including: 20 starts on the test stand (17 September-5 November 1936), 8 starts on the model 212 winged rocket designed by S. P. Korolev (29 April-9 September 1937 and 2 October-8 October 1938), 21 starts on the RP-318 rocket plane designed by S. P. Korolev (16 December 1937-11 January 1938). /187

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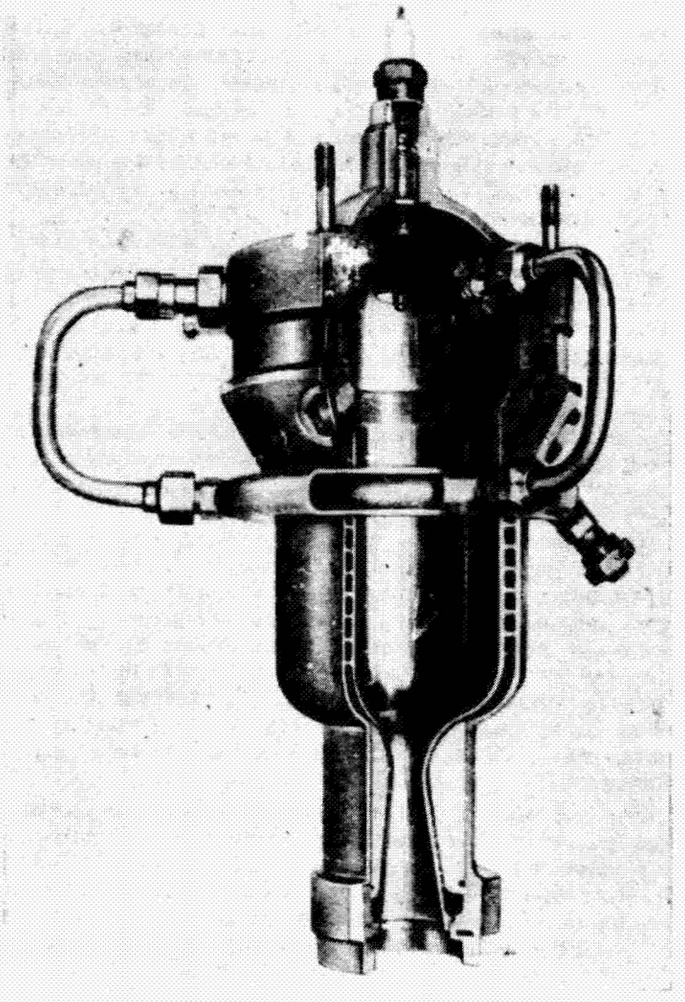

Exterior View of the ORM-65 Engine

During the first ground flame test on the RP-318 rocket plane (16 December 1937), ORM-65 engine No. 1 operated for 92.5 sec; during the next 26 days, 20 more test starts were conducted. The number of starts per day reached 5 (for example, 11 January 1938).

ORM-65 engine No. 2 was tested on the RP-318 and 212 16 times; during its sixth start, it operated on the RP-318 rocket plane during ground testing on 11 March 1938 for 230 seconds; after adjustment operations on the rocket plane, the ground flame testing of ORM-65 No. 2 continued. Between 3 February and 15 September 1938, 9 starts were conducted. This engine was started twice during flying tests on the 212 winged rocket on 29 January

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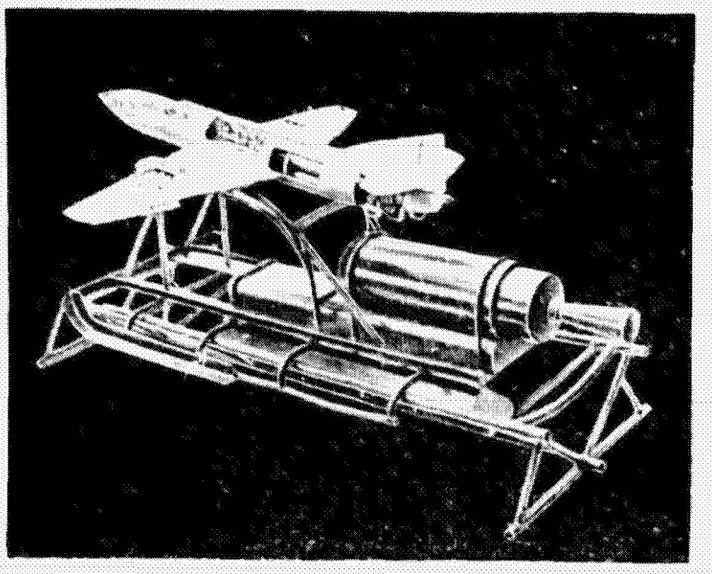
1939. According to the flight tests reports, the start-up and operation of the ORM-65 engine were satisfactory.



The ORM-65 Engine on the 212 Winged Rocket with Powder-Fueled Rocket Accelerator

Continuing the traditions of the GDL, the designers of the ORM engines produced rocket engines distinguished by their exceptional reliability.

The oRM-65-A, a modification of the ORM-65, was smaller in diameter.

The ORM-66, an experimental engine with a thrust of 150 kg, was planned and manufactured in 1936; stand tests were conducted in 1937-1938. The ORM-66 differed from the ORM-65 in that it was lower in weight (6.9 kg) and smaller in size, but had increased combustion chamber volume and a welded nozzle elongation compensator.

The increase in combustion chamber volume and decrease in head weight resulted in the fact that after 15 seconds of operation at nominal mode, the head began to glow, and after 25 seconds the engine had to be turned off. The head of the ORM-66 engine was therefore improved by the addition of fins and external fuel-flow cooling.

The ORM-67 was an experimental engine with a thrust of 150 kg, developed and manufactured in 1937. The engine used a light-weight ignition device; the central electrode of the current receiver had a channel used to measure the pressure in the

combustion chamber. In contrast to the ORM-66, the ORM-67 engine could be completely disassembled; the joints between the head, combustion chamber-nozzle and their jackets were sealed with asbestos strips. The head and chamber-nozzle were made of EYa3A steel, the jackets of duralumin. The engine weighed about 5 kg.

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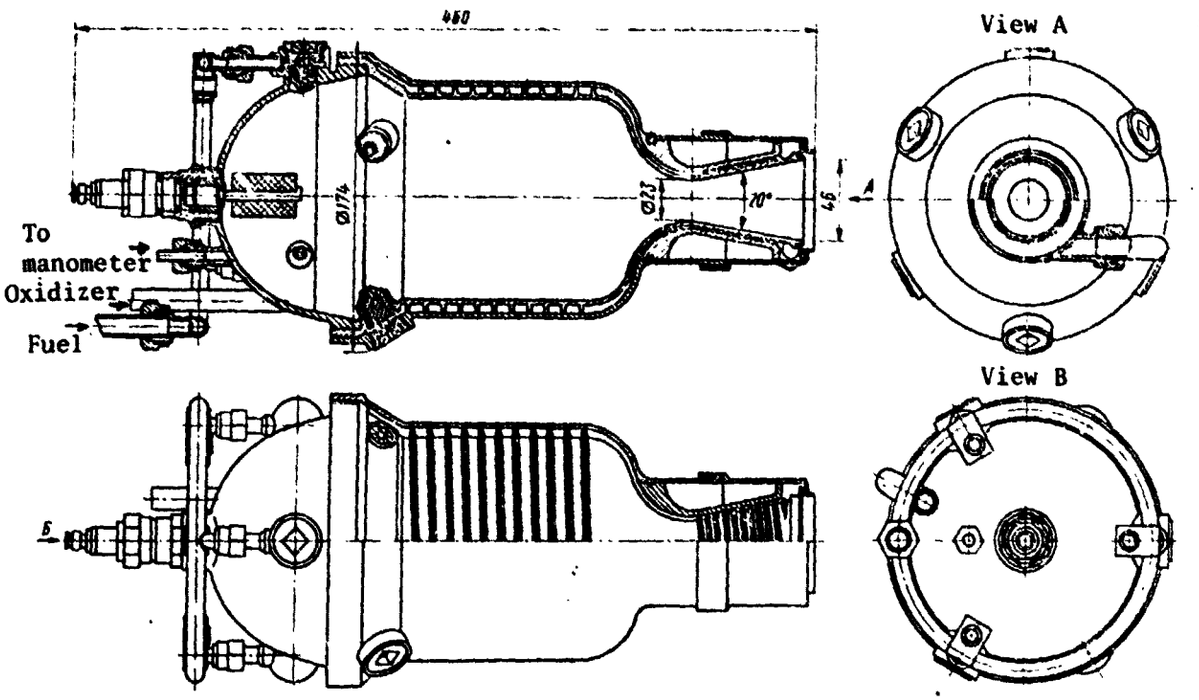

The ORM-66 Engine

The ORM-68 (1937) differed from the ORM-67 in that the head, chamber-nozzle and their jackets were made of duralumin, further decreasing the weight of the device to 3.5 kg. The ORM-67 and ORM-68 engines underwent only hydraulic testing and development of a new ignition device in early 1938.

The ORM-69 engine was developed in 1938 and differed from the ORM-68 in that larger, fuel-cooled ribs were used on the head and an improved ignition device was fitted, following manufacture and refinement testing in early 1938.

In 1937, the ORM-70 design was developed. This was an experimental engine with a thrust of 300 kg, burning nitric acid-kerosene fuel. The design of the ORM-70 is similar to the ORM-67. Eight sprayers are used. The maximum diameter of the combustion chamber is 200 mm, the length is 500 mm. The material

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used is stainless and low-carbon steel, and duralumin. The engine was manufactured in 1937-1938, but was never tested.

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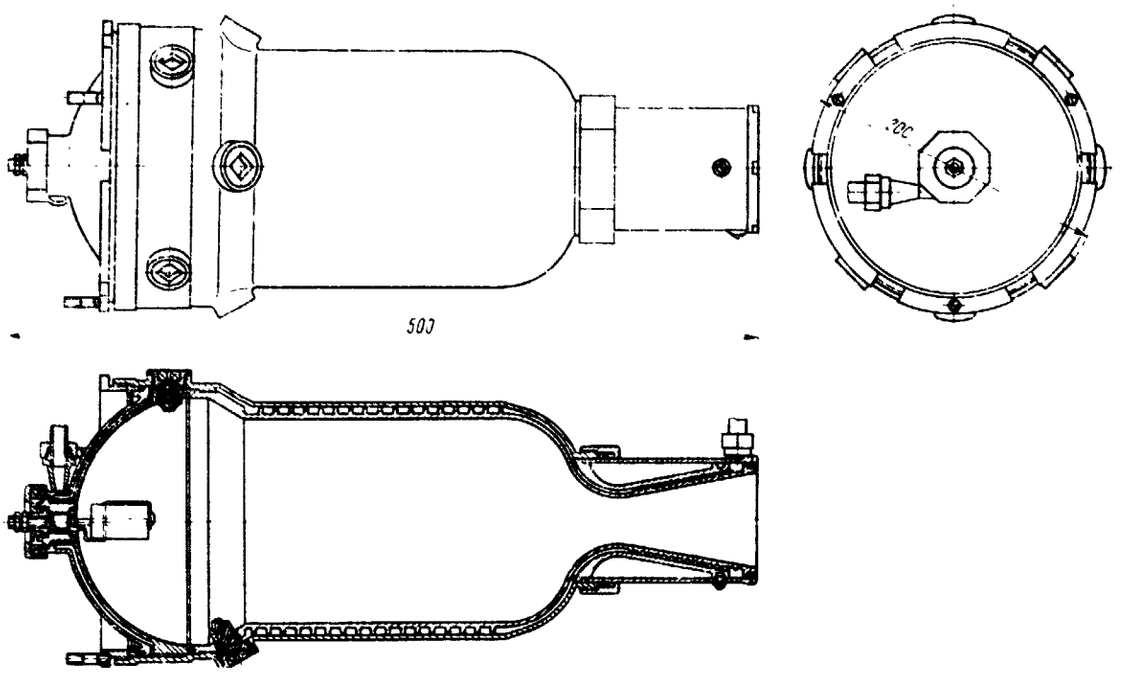

The ORM-70 Engine

The ORM-101 - ORM-102 Engines

These experimental engines were planned in 1937 in order to study the possibility and expediency of using tetranitromethane as an oxidizer. Corrosion testing of various metals in tetranitromethane allowed structural materials stable in this oxidizer to be selected. Experimental tests of the explosion danger of tetranitromethane in operation were conducted. Kerosene was selected as the fuel. The ORM-101, with a thrust of 80 kg, was designed for brief operation. The ORM-102, with a thrust of 100 kg at the same combustion chamber pressure (28 atm) was fully cooled. The engines were manufactured in 1937-1938, but did not undergo flame testing due to the determination that the determination that the use of tetranitromethane was dangerous.

The GG-1 and GG-2 Gas Generators

The gas generators (GG) developed were designed to feed the working fluid for a piston engine or turbine. The zones of combustion of the fuel components (nitric acid and kerosene) and the

zones of mixing with the cooling agent (water) were separate; diaphragms were used to separate the liquid films from the walls of the chamber. Due to the requirement for high purity of the gas produced, preference was given to a two-chamber system, although a one-chamber version was also constructed and underwent stand flame testing.

In the GG-1 gas generator, the fuel components were sprayed into the combustion chamber by 6 sprayers: three oxidizer sprayers fed through the lower circular collector, three fuel sprayers fed through the upper circular collector; water was sprayed in through the two top sprayers. The gas generator was designed for internal cooling of the walls by a protective film of fuel components. Overheating of the combustion chamber walls next to the sprayer belt and connecting collar between the chambers (to 700° C) required that external flow cooling of the spirally ribbed walls of the chamber with water, which was then sprayed into the chamber, be used; the GG-1 passed acceptance testing in this form. /193

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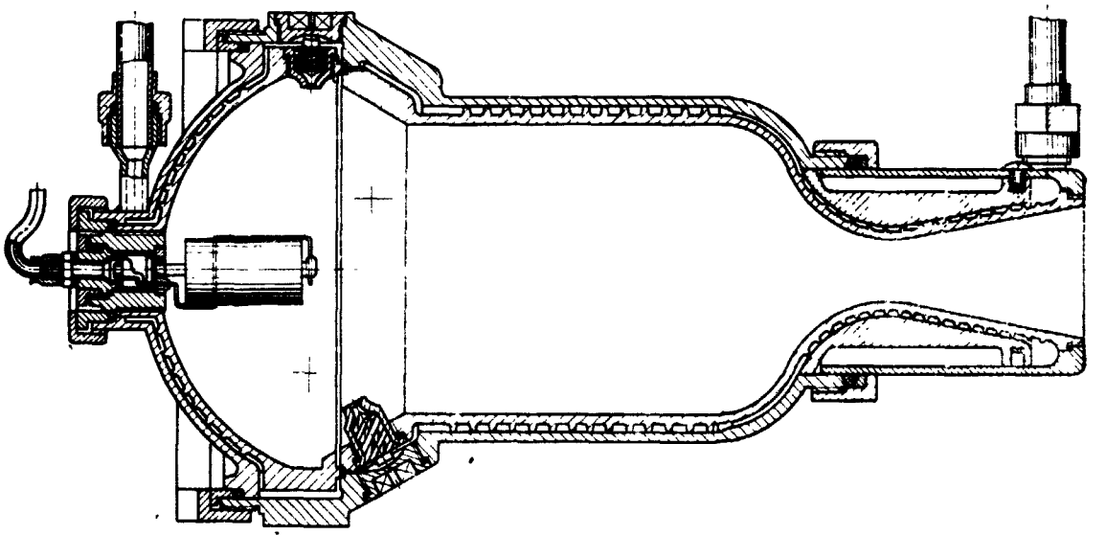
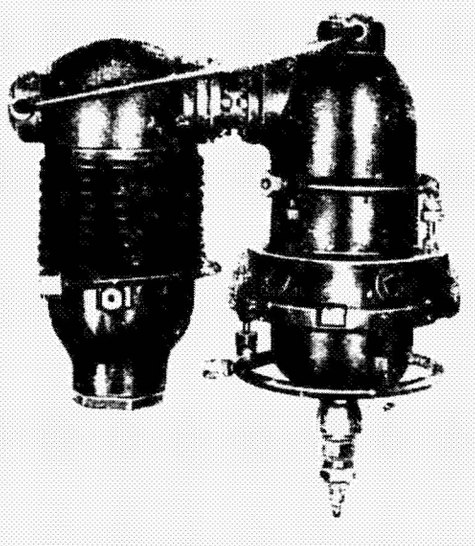


The ORM-102 Engine

Design and dimensions of the GG-1: material of combustion chambers, mixing chambers and sprayer nipples -- EYa3S; of jackets and collectors -- ST4; of sprayers and tubing -- duralumin. Jackets sealed with asbestos cord soaked in liquid glass. The GG-1 was started after a signal lamp or automatically, with simultaneous injection of fuel components and water. In the winter, antifreeze (75% water and 25% ethyl alcohol) was used in place of water.



The GG-1 Gas Generator

The output of the GG-1 was 40-70 ℓ/sec gas at 20-25 atm and 450-580° C. The gas generator operated stably on nitric acid and tractor kerosene with water injection. The total consumption of oxidizer and fuel was 0.15-0.17 kg/sec, of water -- about 0.20 kg/sec. The fuel component feed pressure was not over 30 atm. The weight of the gas generator was 20 kg. After 1 hour 46 minutes operation, the gas generator showed no essential defects and was capable of further operation. The time of continuous operation was up to 15 minutes (determined by tank capacity). The gas generator could operate briefly (minutes) at gas output temperatures of up to 700-800° C. The gas produced by the gas generator was of high purity and was colorless; according to gas analysis data, it contained no nitric acid or nitrogen dioxide and did not cause corrosion of copper alloys during operation. The chemical composition of the gas produced by the GG-1, according to results of analysis of a sample taken during acceptance testing at α = 0.88 with a pressure in the GG of 23 atm, gas temperature 490° C, after condensation of water, was as follows, in vol. %: /195 NO -- 20.2%, CO_2 -- 21.8%, CO -- 15.2%, O_2 -- 0%, remainder nitrogen, acidity -- traces.

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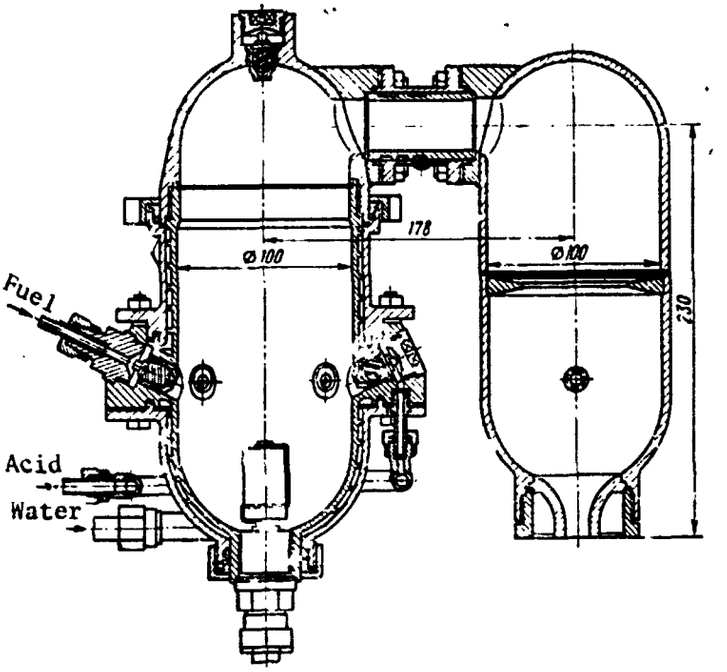
The GG-1 gas generator was developed during 1935 and 1936 and successfully passed official stand testing on 27 August 1937.

In 1937, a design of a L-shaped two-chamber gas generator, the GG-2, producing up to 100 ℓ/sec gas at a pressure of up to 30 atm and temperature of 450-600° C was developed. The GG-2 was a further development of the GG-1 gas generator. The fuel component feed pressure of the GG-2 was 36-40 atm; the weight of the gas generators was less than 30 kg; the GG-2 was not constructed.

The RDA-1-150 Engine

The RDA-1-150 engine was developed under the leadership of L. S. Dushkin and A. V. Pallo for nitric acid plus kerosene fuel and was designed to develop 150 kg thrust. The centrifugal sprayers, eight main fuel sprayers and two start-up sprayers, were placed on the uncooled spherical head so that the streams of fuel

components were directed toward the center of the hemisphere, to the zone where the head was connected to the cylindrical portion of the chamber. In the upper portion of the head, on the axis of the chamber, was a throat for the igniter device. The head was fastened to the cylindrical portion of the chamber by means of a thread. At the junction point there was a linear expansion compensator gland.



Cross-Section of the GG-1 Gas Generator

The cylindrical combustion chamber had double spiral cooling ribs. The nitric acid entered the cooling cavity at the point of connection of the chamber to the nozzle, then passed through the apertures in the head directly to the sprayers.

The removable nozzle was cooled by kerosene which entered the jacket at the nozzle end and left at the point where it was connected to the chamber. The outside surface of the nozzle carried a double spiral set of notches, the lands of which were in tight contact with the nozzle jacket. In the lower portion of the nozzle (at the exit plane) was a linear expansion compensator gland.

The basic difference between the RDA-1 150 and the ORM-65 was the altered placement of the fuel sprayers in the engine head. Whereas in the ORM-65 the fuel components were sprayed radially or at a slight angle away from the nozzle, in the

RDA-1-150, all of the fuel was directed toward the center of the chamber, toward the nozzle, and the sprayers were located around a circle at identical angles to the chamber axis. However, this difference caused a significant reduction in the primary characteristics of the engine. /198

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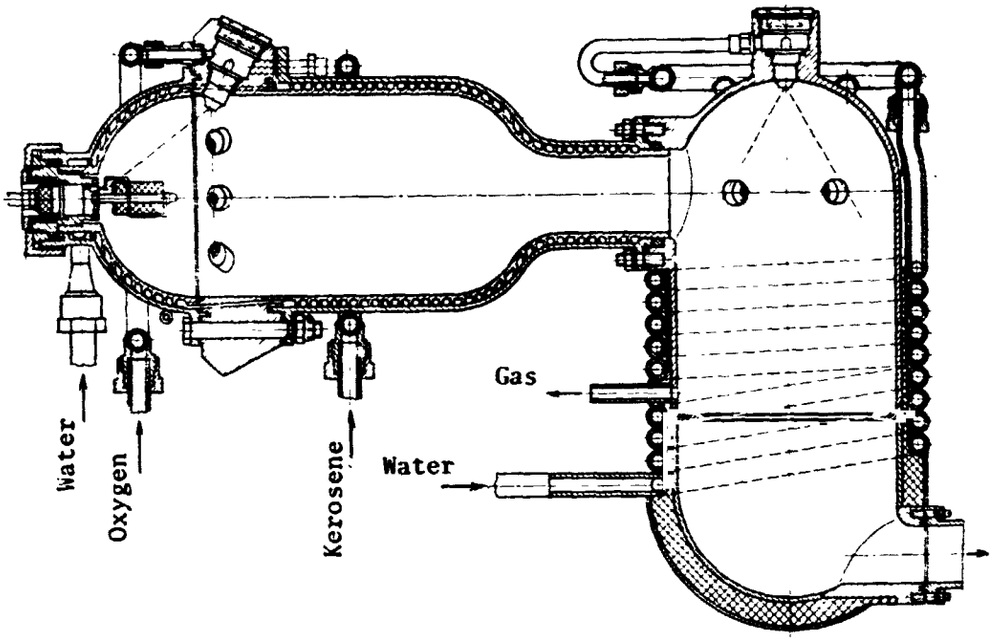

Cross-Section of the GG-2 Gas Generator

Stand tests of the RDA-1-150 engine began in the second half of 1939. Two identical models were tested, and about 20 starts were made. In January of 1939, one of these models operated 200 sec without damage. During March through September of 1939, combined tests were performed on a rocket plane, together with the fuel feed system and the control system. During this period of time, the engine withstood 108 flame tests, showing the following results: thrust 140 kg (compared to 175 kg for the ORM-65), specific impulse with chamber pressure 18 atm reached 186 sec (as compared to 210-215 sec for the ORM-65).

As a result of the tests of the RDA-1-150, reliable operation of the engine was achieved, and the procedure for start-up, mode control and shut-down of the engine from the cabin of the rocket plane was developed. Experience was gained in the operation of the engine, allowing the experimenters to begin flight testing of the engine following the ground testing.

The first flight tests of the RDA-1-150 engine were conducted by pilot V. P. Fedorov on 28 February 1940, using the RP-318 rocket plane.

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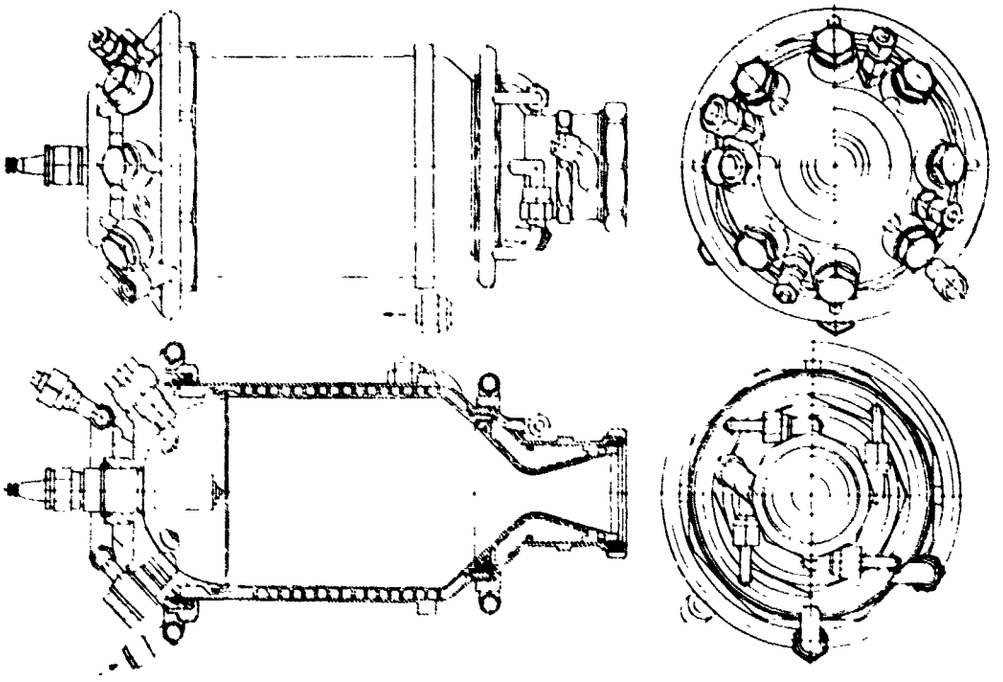

The RDA-1-150 Engine

An ordinary aircraft with a piston engine towed the rocket plane to an altitude of 2000 m, where the pilot disengaged the rocket plane from the piston-engine plane, and began to glide. After separating a sufficient distance from the tow plane, the test pilot turned on the rocket engine, which continued to operate until its fuel was fully expended. After shut-down of the engine, the rocket plane continued to glide and landed at the airfield.

This was the first manned flight of a flight vehicle with LRE in the USSR.

The RDA-300 Engine

The RDA-300 engine was designed to develop a thrust of 300 kg, and was also intended for the RP-318 rocket plane, in order to allow independent take-off, i.e., without requiring a tow plane.

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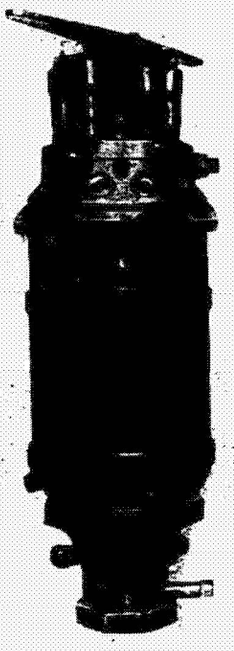
The RDA-300 engine, developed in 1939 under the leadership of L. S. Dushkin, differed from the RDA-1-150 only in its dimensions. In order to increase the specific impulse to 200 sec, the design pressure in the RDA-300 was increased. By the middle of 1939, the planning and manufacture of the engine were completed. At the same time, another version of the RDA-300 was

developed, with basic design changes based on the results of testing of the RDA-1-150. The reliability of the cooling system was increased by the use of both fuel components; the start-up conditions and quality of mixture formation were improved.



The RDA-300 Engine

The RDA-300 engine which passed flame testing had a head which differed significantly in design and operating principle from the heads of all earlier models. It had spiral sprayers, directing the stream toward the nozzle and assuring fine atomization and good mixing of the components. The nitric acid from the cooling cavity of the cylindrical portion of the chamber passed through channels in the head to the needle-type stop valves, which controlled two sprayers each.

Similarly, kerosene from the cooling channel entered needle-type stop valves for the kerosene sprayers.

The head carried the main sprayers and the start-up sprayers, assuring reliable start-up of the engine.

The fuel components were fed in /200
through the start valves directly from the tanks independently of the main mass of fuel which flowed through the cooling cavities of the combustion chamber and nozzle.

The mixture sprayed by the start-up sprayers was ignited by means of two ignition devices. In the central portion of the head there was a glow plug, and at an angle of 20° to the axis of the motor there were two electrodes on the head, between which a spark jumped when the engine was started. The engine was started in two stages. First, the start-up sprayers were used to create a flame in the head, then the valves were opened and the fuel components in the cooling cavities of the chamber and nozzle were fed in under pressure through the main sprayers. The quantity of fuel delivered and, consequently, the thrust of the engine depended on the lift of the stop valve needles.

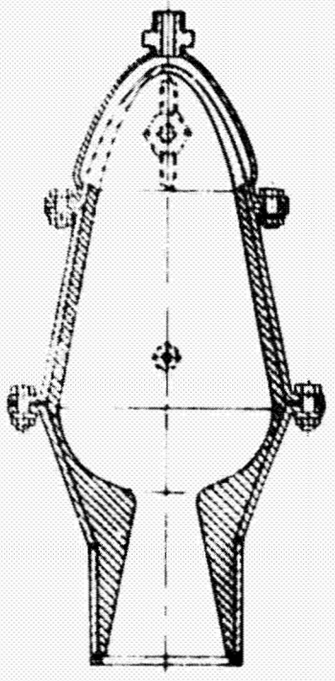
Tests in 1939 and 1940 showed that with a pressure of 19.5 atm, the engine developed a thrust of 280 kg and a specific impulse of 202 sec. The duration of each test was 9 to 150 sec. The fuel consumption in the starting mode was 0.12 kg/sec. The engine never went through flight testing.

3.4. Oxygen LRE

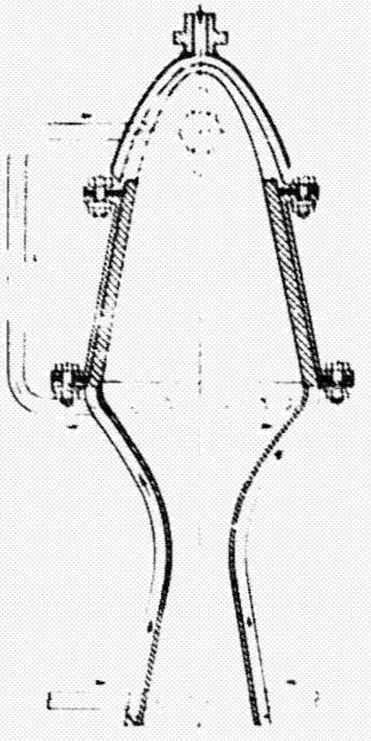
Oxygen engines planned at GIRD developed thrusts of only up to 70 kg with specific impulses of up to 175 sec and did not achieve extended reliable operation; at RNII, the required thrust of oxygen engines was 150-300 kg. In order to achieve this, it was necessary first of all to improve the mixture formation conditions, to increase the pressure in the chamber and to provide reliable cooling.

The 12K Engines

In the first version, the 12k engine used certain solutions realized in the 02 and 10 engines of GIRD: a prechamber with jet sprayers, a pear-shaped combustion chamber and external flow cooling with liquid oxygen. In order to increase the reliable operating time of the combustion chamber and nozzle, shaped ceramic inserts were used, which also provided the required shape /201
of the inner contours of the gas path. Ignition was by electric spark plug, introduced into the chamber through the nozzle. The engine was tested in March of 1935. During the 7th second of operation, it burned through in the area of the prechamber, and the ceramic lining cracked.



Third Version of 12K Engine



Fourth Version of 12k Engine

In its second version, the engine had a spherical combustion chamber of stainless steel, allowing a reduction in the specific weight of the structure. The upper hemisphere was lined with ceramic made of roasted aluminum oxide. The lower portion of the chamber and nozzle were made of steel, and were given external flow cooling. The lower hemisphere of the chamber burned through during the 19th second of a test conducted in May of 1935.

In its third version, the engine did not have external flow cooling, but the entire chamber was lined with an aluminum oxide ceramic, the nozzle was lined with a magnesium oxide ceramic. The streams of fuel components were directed against each other, which achieved good mixing. The engine was tested in March of 1935. The engine was shut down after 27 seconds for inspection, which revealed small cracks in the ceramic lining. /202

The results of testing of all three versions of the engine were used as a basis for analysis of the reasons why the required specific impulse and stability of thermal mode of the combustion chamber had not been achieved, leading to the conclusion that in order to achieve a thrust of 300 kg with a pressure in the chamber of about 12-16 atm, the chamber volume would have to be about 2 ℓ. Furthermore, since all of the cooling and heat protection systems tested had failed to assure extended reliable operation, these engine versions were acknowledged to be suitable only for brief experimental operation[1].

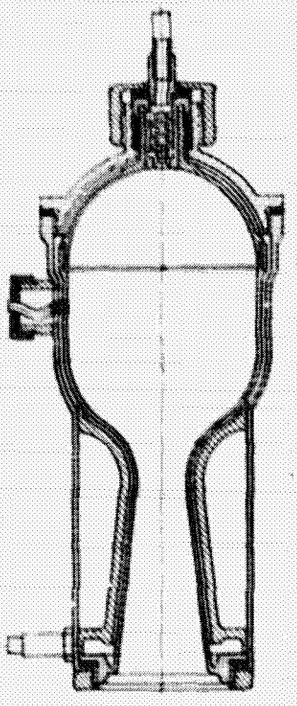
In the fourth version, considering that the region of the critical cross section had failed in earlier tests, the nozzle was an all-metal copper part with external flow cooling but without ribs. In order to avoid the thermal stresses which frequently caused failure of the structure, the nozzle was cooled by the alcohol fuel rather than by the liquid oxygen oxidizer. However, during flame tests the nozzle failed after 30 seconds. This was a result of the insufficient cooling intensity, a result of the low velocity of movement of the alcohol through the cooling channels.

The 205 Engines

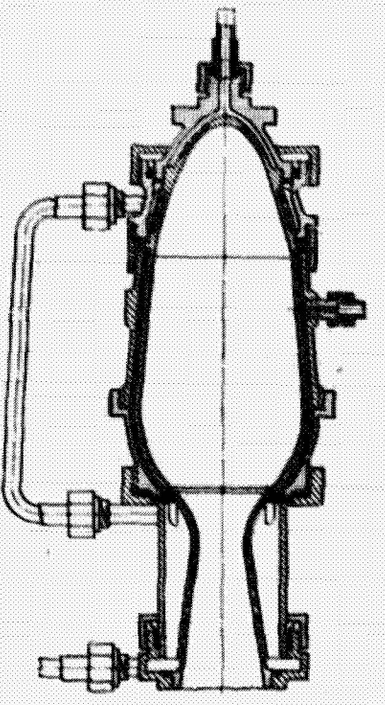
Based on ballistic planning of wingless rockets and the results of flame testing of the 12K engines, it was considered necessary to assure constant thrust, decrease the amplitude of fluctuations of chamber pressure, reduce the time required to reach the nominal mode to 2.5 sec, increase the specific impulse to at least 215 sec at a chamber pressure of 20 atm, provide

[1]Later, the 12K engine was tested on the Aviavnito rocket.

continual operation of at least 25 sec and reduce engine weight to not over 4 kg. /203



First Version of the 205 Engine



Third Version of the 205 Engine

In accordance with these requirements, the 205 engine was made in several versions. In the first, all-metal version, jet-type sprayers for the fuel and one central spiral sprayer for the oxidizer were used, since these sprayers had been fully tested on the ORM engines. The chamber and nozzle were cooled by alcohol; in order to lighten the structure, duralium was used for a number of parts. Chambers were tested with nozzles made of duralumin and of copper. The experiments showed that with a speed of cooling alcohol of about 6 m/sec, an engine with a duralium nozzle failed after 10 sec, with a copper nozzle -- after 20 sec.

A number of special studies were performed at RNII to determine the causes of failure of the nozzles and find reliable methods of cooling. It was established in particular that the most vulnerable point was the region of transition of the spiral path to a smooth path. Although the cooling conditions were improved in the second version, the nozzle still failed during flame testing during the first few seconds of operation of the engine. /204

In the third version, the velocity of the alcohol in the cooling space was increased to 20 m/sec. In late December 1936, a number of tests were performed with nickel-plated copper nozzles. During the first test, fearing a failure, the experimenter shut down the engine after 38 seconds, during which time the engine had developed a thrust of 94 kg and a specific impulse of 206 sec with a chamber pressure of 12.5-15 atm. Inspection of the engine revealed slight damage. A second test was less successful -- the engine failed after 27 seconds. The duration of the third test was 44 seconds. During this test, with a chamber pressure of 13.5 atm, the engine developed a thrust of 96 kg and a specific impulse of 213 sec.

As a result, it was decided to use ribbed cooling channels and a sprayer head which would provide better atomization and mixing the fuel components.

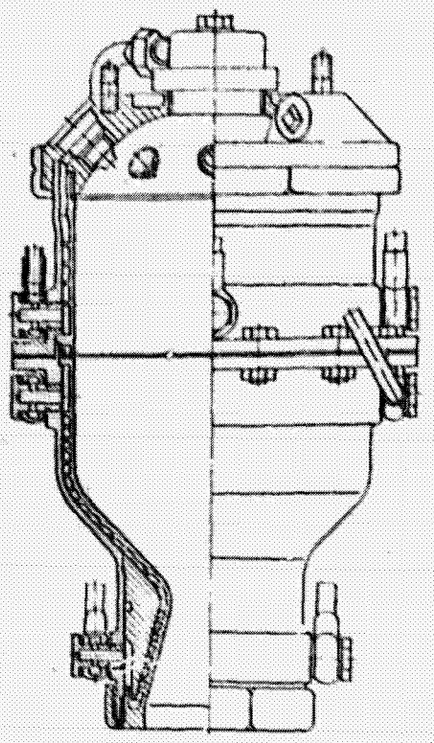
The RDK-1-150 Engine

The RDK-1-150 Engine, burning liquid oxygen and ethyl alcohol, was intended to test experimentally the possibility and expediency of using oxygen engines in manned flight vehicles. The designers of the engine, L. S. Dushkin and V. A. Shtokolov, selected the G-14 glider for the RDK-1-150, since this glider had a greater load carrying capacity than the RP318, so that larger fuel tanks could be carried.

Whereas the 12K and 205 engines were based on the GIRD 02 and 10 engines, the RDK-1-150 engine made extensive use of the experience gained at RNII in the development of nitric acid engines.

The head of the RDK-1-150 was a hemisphere with 12 centrifugal sprayers for oxygen and a sprayer unit with 6 alcohol sprayers. Two aviation spark plugs were placed between the sprayers for ignition purposes. Due to the low power of this ignition source, in later models pyrotechnical and chemical ignition were used. /205

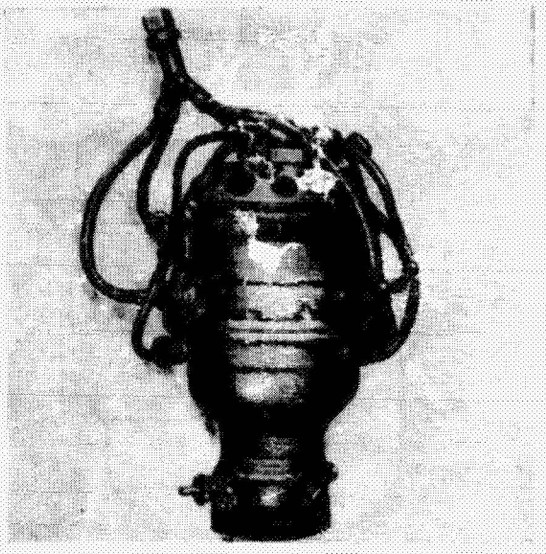
The combustion chamber consisted of the inner wall, made of copper, and the jacket, made of duralumin. The copper chamber carried a quadruple spiral rib pattern on the outside to guide the flow of the liquid oxygen. The nozzle and chamber were joined by means of flanges. The nozzle consisted of an inner copper wall, a duralumin jacket and a sleeve. The quadruple spiral ribbing on the outer surface of the wall formed channels for the cooling fluid. The fluid used to cool the nozzle was alcohol, which passed through the nozzle cooling channels, then through tubing into the upper cavity of the chamber head and thus into the sprayers. /206



The RDK-1-150 Engine

The RDK-1-150 engine passed a series of flame tests in May of 1938. During the first tests, the chamber burned through in areas where the streams of oxygen struck the walls. After several changes in design of the head, these failures were stopped. During tests in September of 1938, a chamber pressure of 10 atm was reached, providing a thrust of 150 kg and a specific impulse of 200 sec.

In January of 1940, the engine passed flame testing on a model of the G-14 glider, operating at the design thrust level for 72 sec with a chamber pressure of 11 atm. Comparisons of the RDA-1-150 and RDK-1-150 engines, designed for manned flight vehicles, as to their operational, economic and weight characteristics indicated that each could find its own area of effective application.



The RDK-1-150 Engine

The Engine of P. I. Shatilov /207

In 1935-1936, an engine designed by P. I. Shatilov was developed at RNII.

The plan for this engine included several promising ideas. For example, the fuel components entered the inner cavity of the combustion chamber through tiny apertures distributed over the surface of the combustion chamber. The fuel components were fed to these apertures through longitudinal channels formed by the wall of the combustion chamber and its jacket. The fuel components mixed next to the chamber walls, upon leaving the tiny channels. The fuel components flowed out of the tiny channels in a tangential direction, creating a boundary layer next to the wall to

improve the protection of the walls from high heat fluxes.

The liquid oxygen evaporated in the cooling system was sent to the turbine which drove the fuel pump. The oxygen from the turbine was then sent to the combustion chamber in gaseous form.

Thus, the engine of P. I. Shatilov featured the progressive ideas of the porous combustion chamber and a feed system which allowed the spent turbine gas to be burned.

RNII encountered technical and technological difficulties which were insurmountable at the time in its attempts to construct the P. I. Shatilov engine. Therefore, work on this engine was halted in 1936.

3.5. Developments by Design Bureau No. 7 (KB-7)

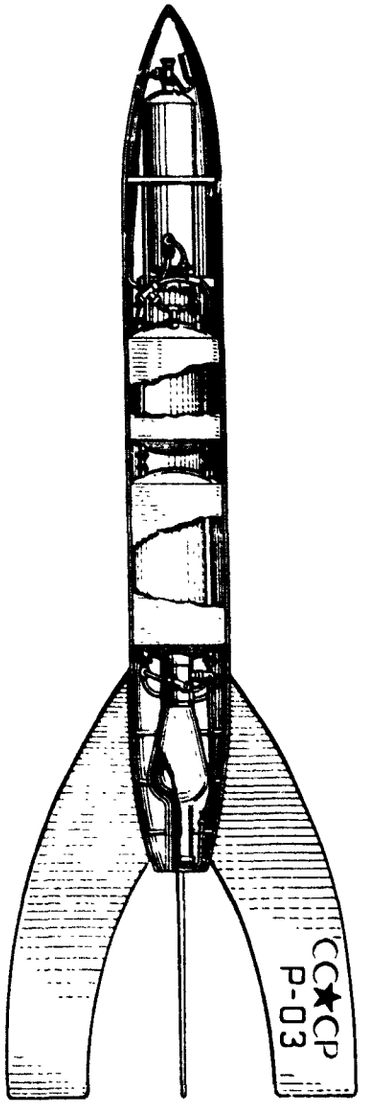
In August of 1935, a design bureau (KB-7) was set up in the Main Artillery Administration of the Red Army. This bureau included some of the workers from the oxygen team of RNII plus a number of specialists from various general machine building enterprises. KB-7 was headed by L. K. Korneyev; other workers included A. I. Polyarnyy, E. P. Sheptitskiy, P. I. Ivanov, M. G. Vorob'yev, A. S. Rayetskiy and other. KB-7 had a small production base, two laboratories and a testing station. The laboratories and testing station were equipped with modern (for the time) measurement apparatus, since the flame test stand of KB-7 was considered a very significant installation.

Together with the development of LRE, KB-7 performed flight testing of rockets burning liquid oxygen-ethyl alcohol fuel. First, the planning of the LRE was based on the experience of the work with the 02 and 10 engines (GIRD), then on certain achievements of the teams at RNII. /209

The first models of engines in the M family were designed for the R-03 and R-06 rockets. They were most reminescent of the 10 engine of GIRD, with its pear-shaped combustion chamber with ceramic lining and prechamber with jet-type sprayers. One such engine, with a design thrust of 100 kg, was installed on the R-03 rocket.

The length of the rocket was 2.18 m; diameter 0.2 m; launch weight 30-33.5 kg, including 8 kg of oxygen and 4.5 kg of alcohol; extractive fuel component feed was used.

The first launch of the rocket was conducted in April of 1937. After modification of the rocket (it was now called the R-03-02), it was tested with the same engine in flight 6 times. /210



The R-03 Rocket

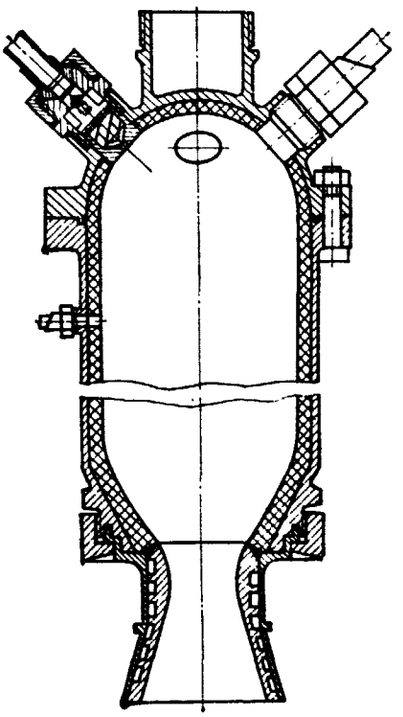
The R-06 rocket, the first version of which was planned and manufactured in 1934 by A. I. Polyarn'iy for Osoaviakhim, utilized an engine with a cylindrical combustion chamber and a peaked head. The nozzle had a shaped ceramic insert. After modernization at KB-7, the rocket, with a launch weight of 39 kg, was tested a number of times in 1937-1938 with an engine with a design thrust of 100 kg. /208

A number of versions of the M-29 engine were planned for the R-05 rocket, made in 1938-1939 on order from the Geophysics Institute of the Academy of Sciences USSR. In this engine, both fuel components entered the combustion chamber through spiral sprayers with ball back valves. The fuel was extracted from the tanks by means of a powder pressure accumulator developed by A. B. Ionov. The combustion chamber was conical in shape; the head had a ceramic liner. In other versions, the chamber was cylindrical. The nozzle of the engines had external flow cooling by alcohol flowing through a spiral ribbed channel space. The M-29s engine, which passed stand testing, was designed for the R-05 rocket; the design thrust was 175 kg.

KB-7 developed and tested a combined engine which was transferred from RNII. As a result, the M-17 combined engine, an LRE which carried a charge of solid fuel in its combustion chamber, was planned under the leadership of V. S. Zuyev. The solid fuel burned first, providing high thrust for several seconds (first stage). At the end of the burning of the solid charge, liquid fuel components were fed to the combustion chamber and the engine went over to its main operating mode (second stage). The solid fuel charge of the M-17 engine consisted of two one-channel caps and was held in place at the nozzle end by an easily burned oak plug. Black powder igniters were placed at both the nozzle and head ends. The head of the chamber carried spiral sprayers with ball back valves. The exit apertures of the sprayers were plugged with powder on the chamber end. The nozzle was flow-cooled by alcohol, which began moving when the engine shifted to the LRE mode. During combustion of the solid fuel, the powder /211

plugs and the oak plug were fully consumed. The engine passed testing in 1938.

Since the volume of the combustion chambers of modern LRE would allow the placement of a solid fuel charge incomparably small in comparison to the quantity necessary for first stage operation, combined engines have not been further developed.



One Version of the M-29 Engine

The activity of KB-7 did not yield the expected results, and it was disbanded in 1939, its test stand and equipment transferred to RNII.

The first great step of mankind will be when he flies beyond his atmosphere and orbits the Earth.
K. E. Tsiolkovskiy

Chapter 4. Liquid-Fueled Rocket Engines for Aviation /212

The Great Patriotic War, from its very beginning, required increases in the speed, altitude and maneuverability of all types of combat aircraft.

One solution to this problem was the use of rocket engines as primary or supplementary (accelerator) engines. Therefore, the suggestion of leading specialists in the area of rocket technology that LRE be used in this manner was actively supported.

Engines intended to be the main engines for combat aircraft must develop rather high thrust -- about 1000 kg, while reaction accelerators must develop 300 kg or more. These engines were to provide high specific impulse, long-term (totalling several hours) reliable operation, multiple restart capability, plus the capability of being refueled rapidly. Therefore, these engines were only designed to utilize nonvolatile oxidizers.

Liquid-fueled rocket engines for combat fighters (interceptors) were developed at OKB under the leadership of V. P. Glushko, at RNII under L. S. Dushkin and at the Design Bureau of the Peoples Commissariat for the Aviation Industry (NKAP) by a team headed by A. M. Isayev.

4.1. The Liquid-Fueled Rocket Engines of OKB NKAP

In 1934-1938, V. P. Glushko continued to develop LRE (ORM-53-ORM-102) and gas generators (GG-1, GG-2) in the subdivision of /213
RNII which he headed, which had been transferred from GDL and reinforced with additional engineers and technicians -- F. L. Yakaytis, S. S. Ravinskiy, D. P. Shitov, V. N. Galkovskiy and others.

Beginning in 1939, according to a task assigned by the Peoples Commissariat for the Aviation Industry, the team of designers headed by V. P. Glushko began to specialize primarily in the creation of aircraft LRE -- accelerators. By this time, some experience had been gained with such engines, since as early as 1932 GDL had begun development of experimental LRE for aircraft. Plans called for the installation of two LRE with thrust of 300 kg each beneath the wings of an I-4 aircraft.

In 1940-1946, a series of LRE were produced with pump fuel feed: RD-1, RD-1KhZ, RD-2 and RD-3. Some of these engines passed flight and state testing and were put in series production. The planning and development of these engines were preceded by the development of individual LRE plans and plans for subunits. For example, in 1940 the Design Bureau developed a plan for a two-chamber LRE-accelerator with a thrust of 2 x 300 kg for installation on the S-100 aircraft. This engine was to burn nitric acid and kerosene. The fuel components were to be fed by a pump unit driven by one of the main (piston) engines of the aircraft.

During this same year, a single-chamber nitric-acid LRE with a thrust of 300 kg was planned. The turbine pump unit of this engine had a single-stage turbine, a speed reducer, oxygen, kerosene and oil pumps.

In 1940, development was begun on a four chamber nitric acid-kerosene LRE with a thrust of 1000-1200 kg with a single turbine pump unit.

In 1942-1945, this trubine pump unit was constructed, but it was never fully developed, since by this time the testing of gear pumps driven by the main (piston) engine was completed.

A two-chamber L-shaped gas generator, the GG-3, delivering 2 kg/sec gas at 450° C and 25 atm pressure, was planned in 1939-1940 for planned turbines of marine torpedos. The generator burned nitric acid and kerosene, but water was sprayed into the combustion products in order to reduce the gas temperature. All three components were supplied to the generator by means of a supplementary turbine-pump unit. /214

The nitric acid and kerosene were sprayed into the combustion chamber of the generator through spiral sprayers. The combustion chamber of the generator was cooled with water flowing over the spiral ribs in the space between the chamber wall and jacket, then was sprayed into the gas stream in the area where the combustion chamber and mixing chamber were connected. The mixing chamber was also cooled by water flowing through a spiral channel. The water was then fed through centrifugal sprayers into the combustion chamber; here it evaporated, additionally reducing the temperature of the generator gas and cooling the walls of the mixing chamber.

The supplementary turbine-pump unit, designed to feed the generator, consisted of a turbine which drove the working wheels of three rotating blade pumps through a reducing gear unit. The turbine was to be started by a pyrotechnical starter with a cap of trotyl pyroxylin powder. The consumption of gas and vapor for the turbine pump unit amounted to 3% of the delivery of the gas generator; the power of the supplementary turbine was

15 hp at 28,600 rpm; the GG-3 including turbine pump unit weighed 54 kg. The plan was never brought to life.

In 1942, the combustion chamber of an RD-1 engine with pump feed operated for 1 hour and 10 minutes without being removed from the test stand, and served as a prototype for the combustion chamber for the RD-1-RD-3 engines. In 1947, the design of the RD-4 engine, supplied by a turbine-pump unit, was developed.

The RD-1 Engine

The single-chamber RD-1 reaction engine was designed as a supplementary engine -- an accelerator for aircraft in order to briefly improve their flying, speed and altitude characteristics.

The calculated data of the RD-1 are as follows: fuel -- nitric acid (OST-701-41) and tractor kerosene (OST-6460); maximum thrust at ground level -- 300 kg; fuel consumption in maximum thrust mode -- 1.5 kg/sec; pressure in combustion chamber -- 22.5 atm; time of continuous operation at maximum thrust -- 30 min; pump shaft rotating speed -- 2000 rpm; operating time until first disassembly -- 45 minutes.

The RD-1 engine consisted of the following units, separately installed on the aircraft: the engine itself (combustion chamber with starting and control units), located in the tail portion of the fuselage or motor gondola or in the wings of the aircraft; the pump unit, driven by the main engine of the aircraft either directly or through a transmission shaft; the choke valve unit and nitric acid and kerosene lines. The choke valve unit was controlled by the pilot from his instrument panel, which also carried a display and the testing and control instruments. /215

The engine mode control system was supplied by the electric batteries and compressed air cylinders of the aircraft. The engine could be started as many as five times in one flight (limited by capacity of starting tank).

The combustion chamber was mounted on the frame of the rocket engine together with the following units: starting unit, starting carburetor, acid and kerosene filters, acid and kerosene valves and electromagnetic pneumatic control valve. The combustion chamber of the engine consisted of the ignition chamber and the combustion chamber itself plus its nozzle. The ignition chamber was split; its forward half was finned and air cooled, its rear half was cooled by kerosene. The combustion chamber consisted of the kerosene-cooled head, and the chamber-nozzle cooled by nitric acid. A liquid flow gap was maintained between the jacket surrounding the head and chamber-nozzle and the split, shaped inserts. The middle portion of the chamber head carried the

nitric acid and kerosene sprayers, centrifugal, closed type, with a hydraulically controlled needle valve. The bodies of the sprayers were made basically of stellite. The material of the acid sprayers was stellite, of the kerosene sprayers -- EZh-2. The fuel which leaked through the sprayer seals was drained through the blocking valves.

The bolts of the chamber had spring washers to allow temperature expansion of chamber parts without disrupting the seal of the joints. The exit portion of the nozzle was equipped with a gland seal which allowed the nozzle to move relative to the jacket as the temperature changed.

The ether-air starting mixture was fed into the ignition chamber through the starting valve, the kerosene -- through a nipple in the throat of the head jacket, the nitric acid -- through a nipple in the throat of the combustion chamber-nozzle jacket. The combustion chamber carried a glow plug, starting valve, pressure relay, filling and blocking valves. /218

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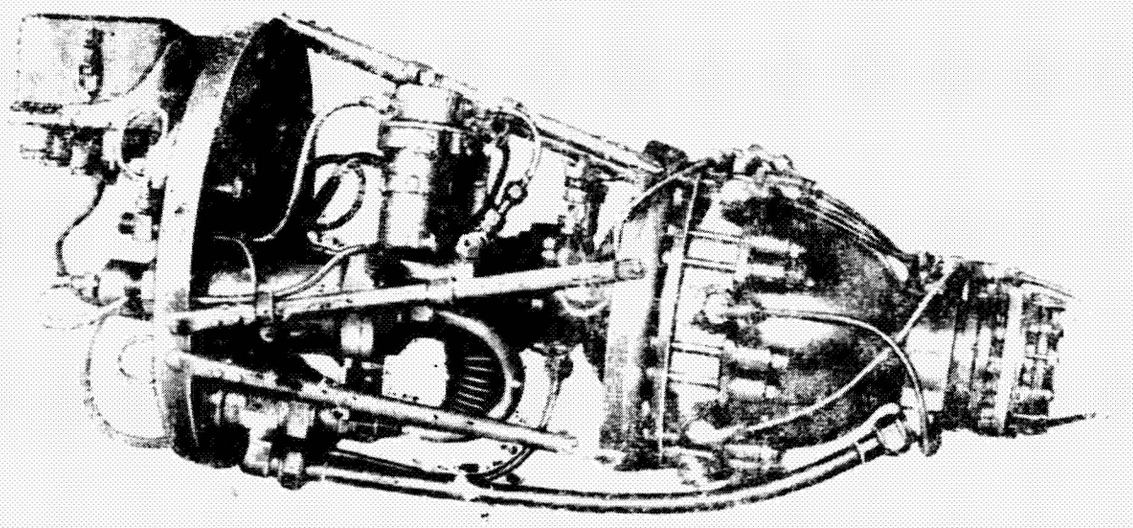

Overall View of RD-1 Rocket Engine

The application of LRE for aviation required that combustion chambers be produced with long operating lives. Therefore, particular attention was given to intensification of cooling. Combustion chamber walls were made using metals with low modulus of elasticity, coefficient of linear expansion, Poisson's coefficient and high values of heat conductivity and strength at the operating temperature. This, in combination with low wall thickness and effective finning on the side wet by the cooling fluid,

was designed to increase the life of combustion chamber walls.

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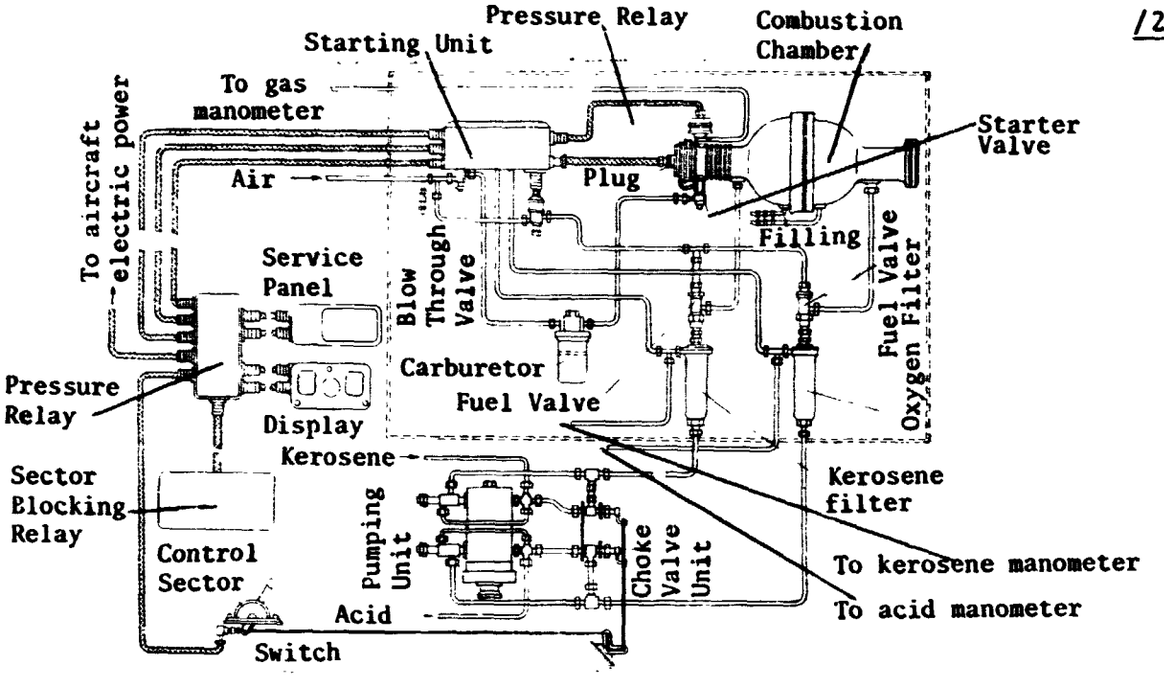

Schematic Diagram of RD-1 Engine Installation

Beginning in 1941, methods were developed for intensification of heat exchange by decreasing the thickness of the boundary layer and elimination of the products of vapor formation and gasification from this layer.

Turbulization of the boundary layer in the most highly stressed sections of the chamber -- the area of inflow and the critical cross section of the nozzle -- was achieved by drilling a system of apertures in the aluminum liner of the nozzle, allowing components to be withdrawn from areas with elevated pressure.

The pump unit was attached to the plate of the front flange. Two stainless steel shafts made in one piece with the gears delivering the nitric acid were placed in the split aluminum body of the pump unit. Splines on these shafts carried the driving gears which delivered the kerosene, and a guaranteed minimum gap was maintained between the teeth of the acid gears, to prevent them from contacting and wearing. Each shaft had three middle-type journal bearings and two ball thrust bearings on one end. A guaranteed minimum clearance was also provided between the body and the ends of the gears of the oxidizer pump. The seal was provided by graphitized asbestos glands. The fluid which soaked through the glands was carried away through internal drilled apertures to the intake cavity of the pump. The pump unit carried

reducing valves, which also acted as safety valves protecting the lines from hydraulic shock.

S. P. Korolev worked in the special design bureay headed by V. P. Glushko (1942-1946 as Deputy Chief Designer for Flight Testing), as did Deputy Chief Designers G. S. Zhiritskiy and D. D. Sevruk, subunit leaders V. A. Vitka, N. N. Artamonov, A. S. Nazarov, G. N. List, N. L. Umanskiy, N. S. Shnyakin, A. A. Meyyerov N. A. Zhel'ukhin, M. A. Kolosov and other highly qualified specialists. /219

In 1944, the special design bureau of A. A. Meyerov developed nitro oils and lubricants which did not react with the nitric acid. They were successfully used in the seals and ball bearings of the RD-1, RD-1KhZ, RD-2 and RD-3 engines.

In order to continue development of the RD-1 under flying conditions and accumulate operating experience, S. P. Korolev in 1943 developed an installation for this engine for the Pe-2 series-produced aircraft. The engine was installed in the tail portion of the fuselage. The pump unit, compensation and drainage tanks were carried in the left motor gondola behind the forward longeron. The engine had dual controls, carried in the pilots cabin and the radio operator-gunner's cabin.

The Pe-2 aircraft conducted 24 flight tests at altitudes of up to 7000 m to develop the ignition system. After ground flame tests were conducted, in 1943 this same aircraft performed 18 start-ups of the RD-1 engine on the ground and 11 in flight. The longest time of continuous operation of the RD-1 engine at full thrust in flight was 10 minutes, determined by the capacity of the fuel tanks.

Flight testing was performed by test pilots A. G. Vasil'chenko and A. S. Pal'chikov, with S. P. Korolev and D. D. Sevruk flying as experimental engineer.

The tests of the Pe-2 aircraft continued in 1944-1943 in order to increase the reliability and altitude capability of the ignition system, with 49 flame tests on the ground and 38 in flight. Preference was given to the system of repeated chemical ignition, which was well-developed by that time, rather than the ether-air ignition system with glow plug and oxygen feed used earlier.

In 1944-1945, the RD-1 engines passed ground and flight tests on fighter aircraft designed by S. A. Lavochkin (La-7), A. S. Yakovlev (Yak-3), P. O. Sukhoy (Su-6) and the aircraft designed by V. M. Petlyakov (Pe-2).

The RD-1KhZ Engine /220

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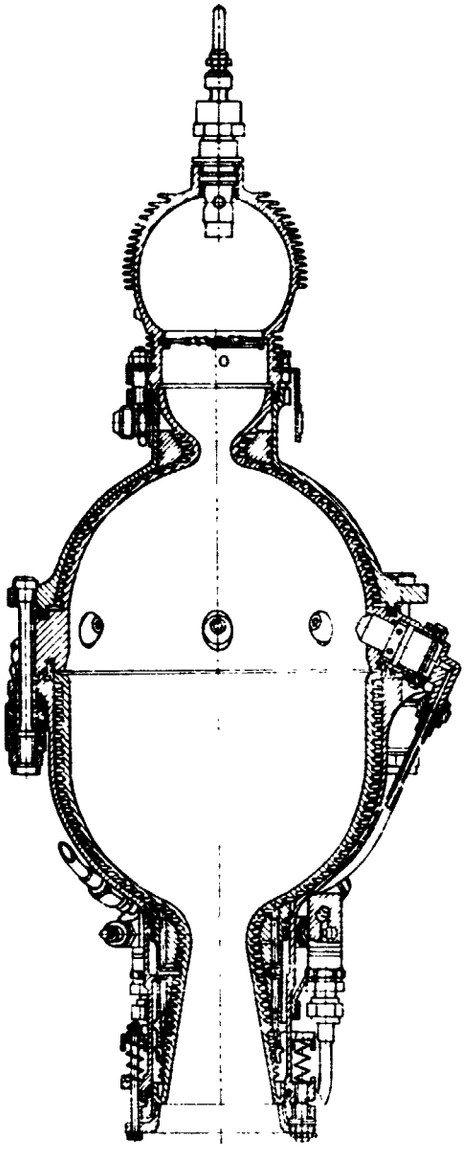
An improved version of the RD-1 engine, with chemical ignition and a number of design innovations, came to be called the RD-1KhZ.

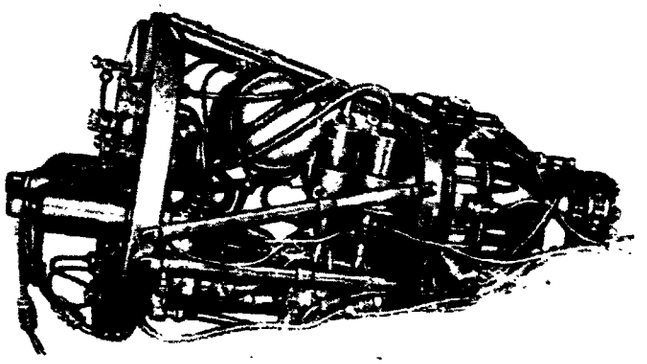
The two internal parts of the combustion chamber of the RD-1KhZ -- the chamber-nozzle, made of EZh-2 stainless steel, and the head, made of heat resistant DPS aluminum alloy -- were connected by means of steel jackets of EZh-2. Between the jackets and the internal parts of the chamber there was a passage for nitric acid in the chamber-nozzle and kerosene in the head. Longitudinal and spiral fins were made on the outer surfaces of the chamber-nozzle and head of the combustion chamber in order to improve cooling conditions. Split aluminum sleeves with an interior profile corresponding to the profile of the chamber parts were placed around the throat of the head and the nozzle.



One Version of the Combustion Chamber of the RD-1 Engine

The kerosene entered the jacket of the combustion chamber head and moved, cooling the chamber, to its middle portion, toward the belt of sprayers. The nitric acid was fed into the jacket around the chamber-nozzle through a nipple at the critical cross section, then flowed first toward the exit plane of the nozzle, then through the spaces between fins between the insert and chamber-nozzle to the sprayers.

The sprayers were located at the head of the combustion chamber, inclined to its axis and directed away from the nozzle. The sprayers were of the same design as those used in the RD-1 engine.



Overall View of the RD-1KhZ Engine

/223

The starting sprayer was located on the axis of the chamber. The starting fuel was fed in through the central portion of this sprayer, with nitric acid fed in through the annular space around this valve.

The starting fuel used in the RD-1KhZ engine was product B23-75, hypergolic in combination with nitric acid, developed at OKB in 1945 by A. A. Meyerov. This product consisted of 75% (by weight) carbonal and 25% type B-70 gasoline. Chemical ignition of the RD-1KhZ engine was first tested on the stand, then on the PE-2 aircraft.

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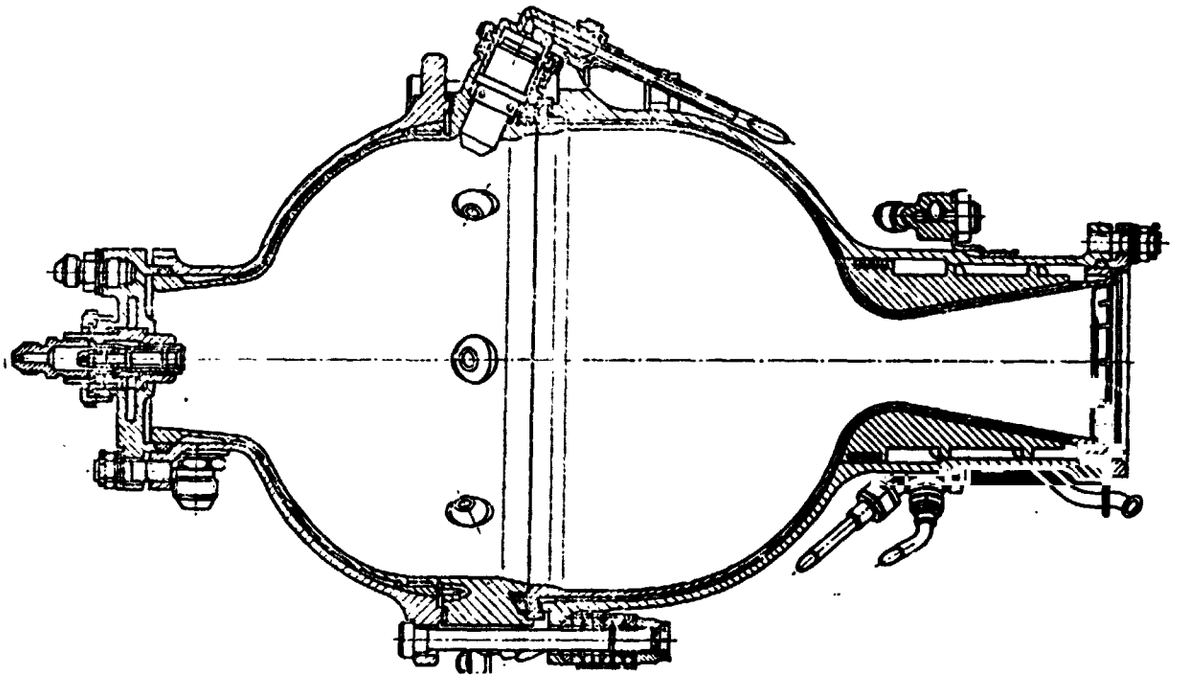


One Version of the Combustion Chamber of the RD-1KhZ Engine

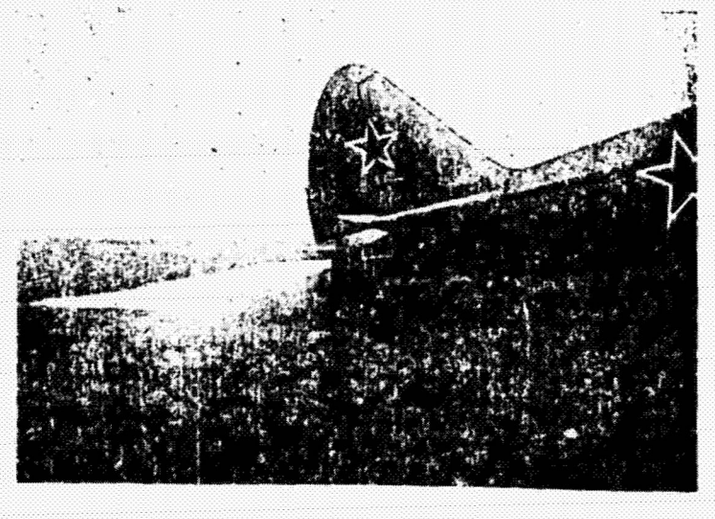
The pump unit of the RD-1KhZ engine consisted of two sections: the nitric acid and kerosene pumps. A gear-type pump was used, the kerosene gears serving as the driving gears, allowing a guaranteed minimum clearance between the teeth and gear ends in acid pump.

Let us study the pneumatic-hydraulic system of the RD-1KhZ engine. The nitric acid and kerosene were fed into the combustion chamber by the pump unit, driven by the main aircraft engine. This drive was by means of a friction clutch, switched on by feeding oil under pressure through an electrohydraulic valve. This valve was opened by the end switch on the engine control sector.

The acid and kerosene delivery lines were connected through the choke valve unit to the intake lines of the pump. With the valves closed, the pump unit developed the maximum feed pressure, corresponding to the maximum engine thrust. When the valves were opened, the acid and kerosene pressure dropped, reducing the thrust. This allowed the thrust of the LRE to be regulated without changing the operating speed of the main aircraft engine.

The safety valves of the pump unit opened when the feed pressure rose above the maximum value and allowed the excess fluid to return to the pump intake line.

The nitric acid and kerosene from the pump unit were fed through filters to the fuel valves, which were opened by compressed air passing through an electromagnetic pneumatic valve, and were closed by springs. As the engine operated, the fuel components were fed through the valves into the combustion chamber, the nitric acid cooling the combustion chamber and nozzle before entering the sprayer, while the kerosene cooled the head.



Testing of the RD-1-KhZ Engine

The engine /225
was started by simultaneously feeding nitric acid and the starting fuel to the starting sprayer. The nitric acid was supplied by the pump unit, the fuel -- from its tank. The starting fuel ignited spontaneously upon contact with the nitric acid, forming the ignition flame. The slight pressure arising in the chamber was used to open the fuel valves and make the switch to the main operating mode.

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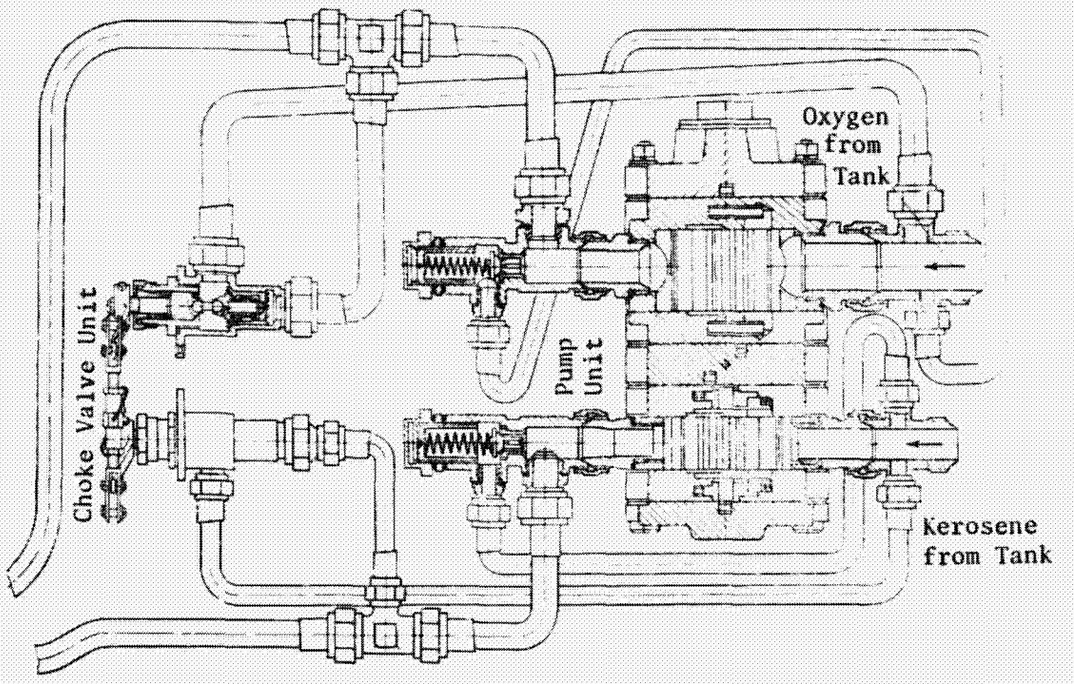
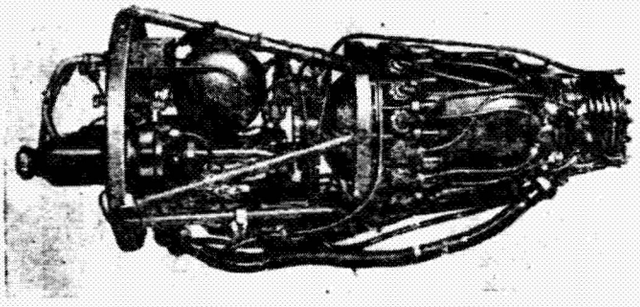


The Pump Unit of the RD-1-KhZ Engine

In order to eliminate hydraulic shocks and explosions in the chamber during start-up (as in the RD-1 engine), the fuel components were continually fed through the cooling cavity, providing a staged start-up mode. The fuel components were drained from the hydraulic lines in the chamber when the engine was shut down. The actual operating life of the RD-1KhZ engine was increased to several hours.

During the deve-opment of the RD-1KhZ engine, 2200 start-ups were performed, 228 of these on the Pe-2 aircraft. At the same time, RD-1KhZ engines were developed for the aircraft of A. R. Yakovlev (Yak-3), S. A. Lavochkin (La-7R and 120R) and P. O. Sukhoy (Su-7). The Yak-3 aircraft underwent plant flight testing in 1945, showing an increase in speed of 182 km/hr at an altitude of 7800 m. The test with the La-7R aircraft achieved a /226
maximum speed of 795 km/hr at an altitude of 6300 m. In 1946, ground tests (58 start-ups) and flight tests (5 start-ups) of the RD-1KhZ engine were conducted on an La-120R aircraft. On 18 August 1946, on Aviation Day, 120R aircraft No. ASh-83 participated in an air parade, flying over Tushino airfield with its RD-1KhZ engine in operation.

The RD-1 and RD-1KHZ engines were series produced during the war. These engines were stand and flight tested, and the RD-1KhZ underwent state testing in 1946.



The RD-2 Rocket Engine

The RD-2 Engine

In order to double the thrust of the RD-1 engine, the length of the cylindrical portion of the chamber-nozzle and number of fuel sprayers were increased in the RD-2 engine, and a number of design changes were made, reflecting the experience gained in earlier investigations.

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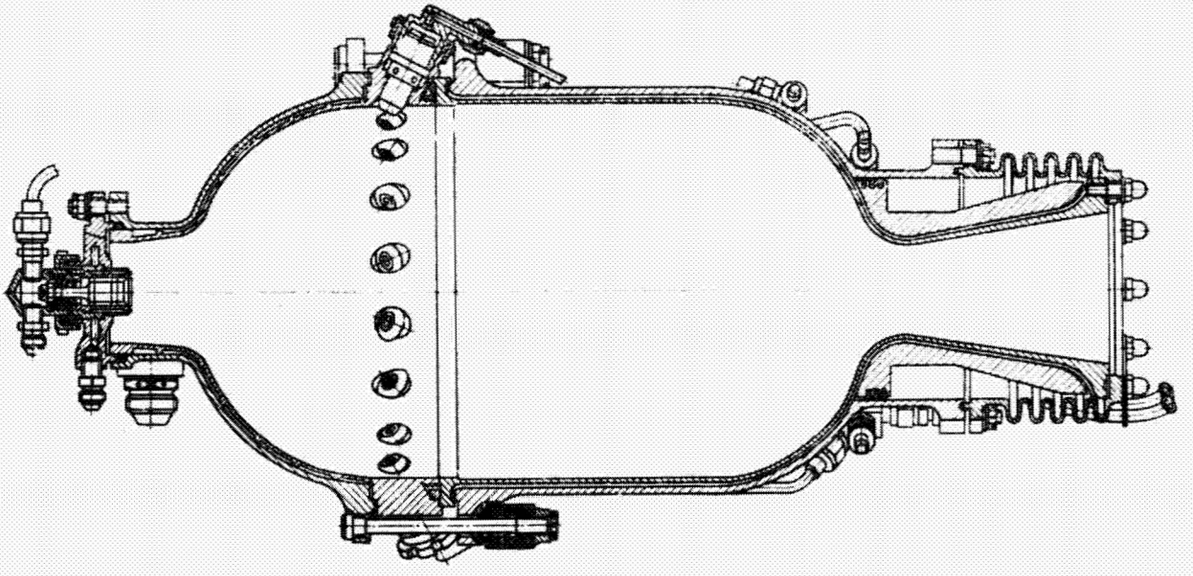


The Combustion Chamber of the RD-2 Engine

The RD-2 engine, like the earlier engines in its family, utilized a gear type pumping unit, differing from the pumping unit of the RD-1KhZ engine in its increased operating speed.

The pneumatic-hydraulic systems of the RD-2 and RD-1KhZ engines were similar, but improvements were made to the system of the RD-2, allowing a softer start-up.

The pneumatic-hydraulic and electrical systems of the RD-2 engine, due to improvements in certain individual elements, were utilized on the RD-1KhZ engine beginning in the second half of 1946. /228

The RD-2 engine passed state testing in 1947 and had an operating life of several hours (the life was limited by pump gear wear).

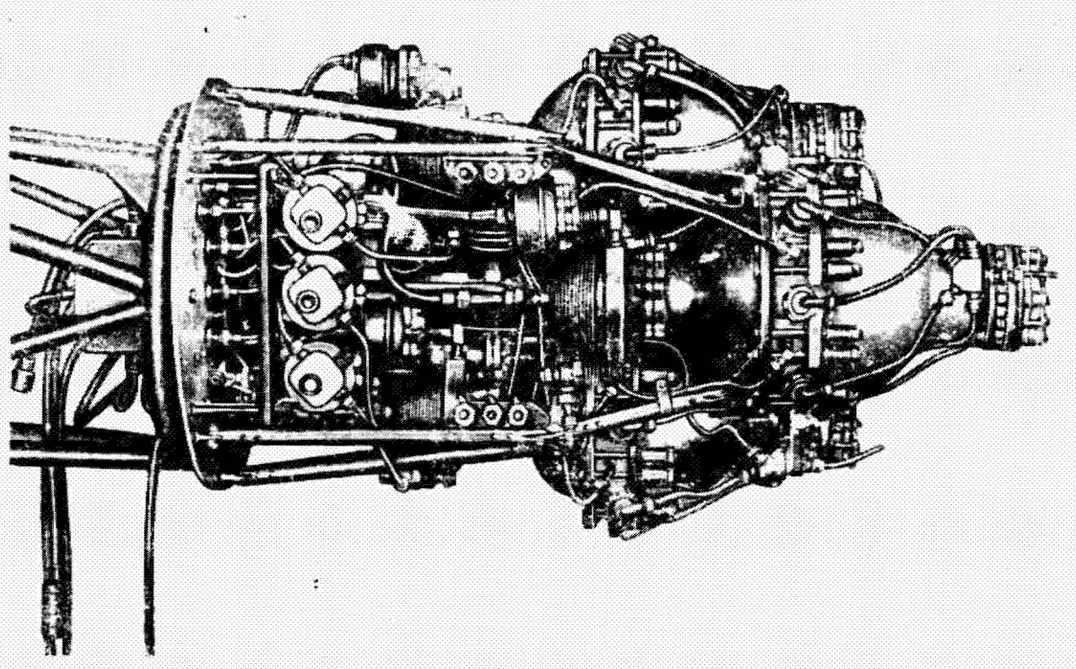
The basic data of the engine are: thrust at ground level 600 kg; fuel consumption 3 kg/sec; time of continuous operation at nominal thrust 6 min (limited by capacity of fuel tanks); guaranteed operating life before first disassembly 1 hour; pressure in combustion chamber 21 atm. Operating speed of pump unit drive shaft 2500 rpm.

The RD-3 Engine

This series of engines was completed in the three-chamber RD-3 liquid fueled rocket engine, which was stand tested in 1944-1945. It was an autonomous engine, since for the first time the nitric acid and kerosene were supplied by a turbine pump unit driven by a gas turbine. The working fluid of the turbine consisted of the combustion products of the fuel of the LRE (nitric acid and kerosene), produced in a special unit -- a gas generator. The RD-3 engine installation included three RD-1 combustion chambers, each of which included a set of service devices -- carburetor, gas pressure relay, filters, fuel valve and electromagnetic-pneumatic control valves, plus filler valves. The thrust of this engine at ground level was 900 kg, in a vacuum -- 1000 kg; the RD-3 could be regulated in thrust from 100 to 1000 kg. In the maximum operating mode (take-off, forced vertical climb and horizontal acceleration), all three chambers were used, with thrust varying in the range of 300 to 900 kg; during horizontal flight, taxiing and landing, only 1 chamber was used, providing a thrust range of 100 to 250 kg. The pressure in the combustion chamber reached 22.5 atm.

Control of the engine was fully automated, and automatic blocking was used to prevent improper starting of the engine. Start-up of the chambers and control of the engine (start-up, thrust regulation, shut-down) were performed by means of a single lever, equipped with an end switch and connected to the choke valve unit of the gas generator. Choking was used to set the proper value of pressure in the gas generator and the corresponding operating speed of the turbine pump unit and, consequently, the thrust of the engine. The design of the engine included remote control of start-up and shut-down. /230

The gas generator included three chambers: the ignition, combustion and mixing chambers. The turbine pump unit consisted of an active single-stage turbine, a reduction gear, oil unit, acid, kerosene and water pumps. The turbine used friction bearings; one of these was water cooled. The maximum turbine shaft speed was 26000 rpm.



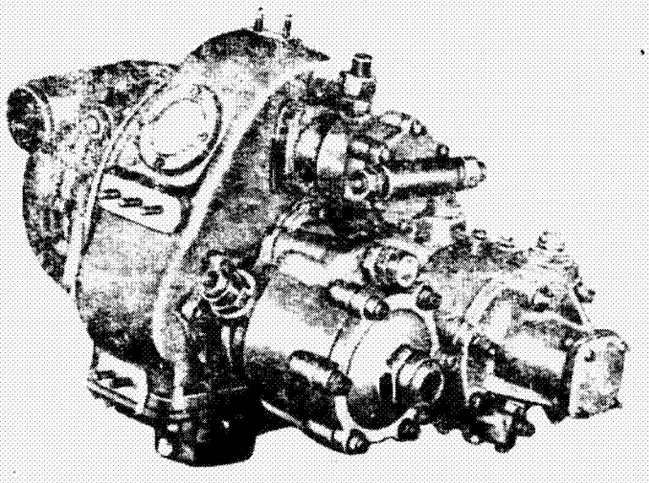
The RD-3 Rocket Engine (Top View)

The first version of the turbine pump unit used a high-speed three-stage centrifugal acid pump, the rotor of which turned in ball bearings. The blade-type kerosene and water pumps of this version were identical in design. Their rotors were balanced, the body was profiled. In order to assure normal operation of the kerosene and water pumps, they were equipped with safety valves. In the second version of the turbine pump unit, all pumps were centrifugal. The fuel components entered the gas generator from the tanks under compressed air pressure.

Thus, between 1940 and 1946, the Design Bureau headed by V. P. Glushko created a series of RD engines, distinguished by a number of advantages. Designed for aircraft, they allowed thrust variation over a broad range and were quite reliable. The engines could be repeatedly restarted. In spite of many hundreds of restarts of an engine without removal from the test stand, the limit of the operating life was never reached. Therefore, the instructions for operation of these engines stated that the number of permissible restarts, within the total operating time of the engine, was not limited. These engines first used grouping of several chambers, which was later widely developed in domestic rocket engine construction, and utilized turbine pump units and gas generators. Finally, the processes of start-up, control and shut-down of the engines were fully automated. The road leading to the development of engines with this degree of sophistication was not an easy one. During development of the electrical and

pneumatic-hydraulic systems of these engines, repeated accidents occu·red, fortunately resulting only in material damage. /231

The RD-4 Engine



Exterior View of RD-3 Engine Turbine Pump Unit

In 1946, the design of the autonomous RD-4 engine, with 1000 kg thrust, was developed. The turbine pump unit of this engine was driven by the products of decomposition of hydrogen peroxide, and the reducing gear was distinguished by its low weight and small size, thanks to the use of high-speed centrifugal pumps for all fuel components. However, this design was not further developed, since OKB then specialized in the development of powerful LRE.

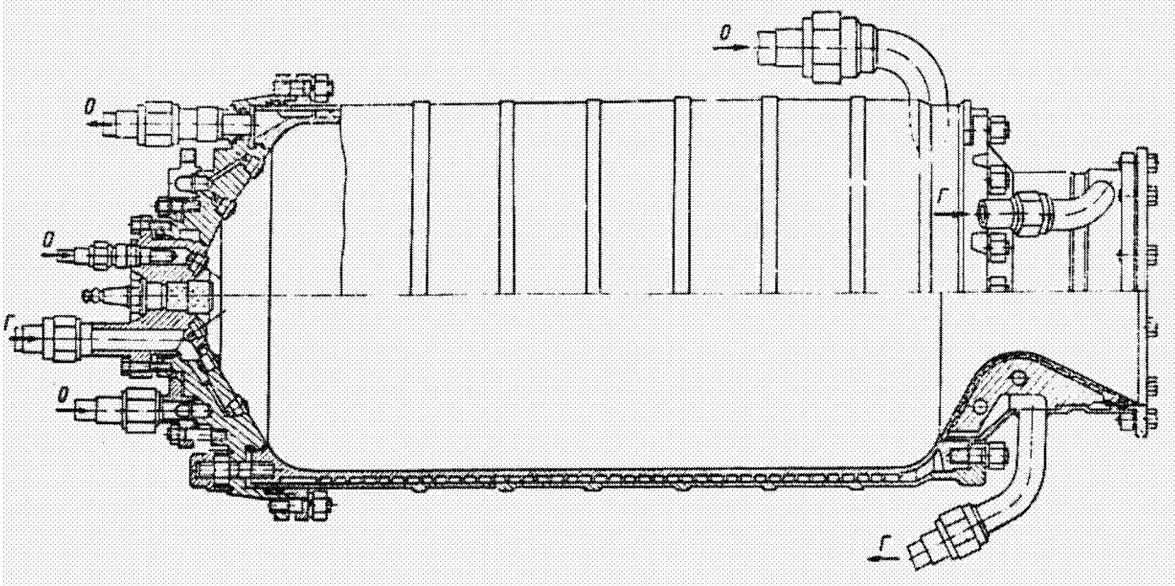
4.2. The Liquid-Fueled Engines of RNII and the NKAP Design Bureau

At RNII, a team of designers headed by L. S. Dushkin developed the D-1-A-1100 liquid-fueled rocket engine, intended for use on an interceptor designed by V. F. Bolkhovitinov, A. I. Bereznyak and A. I. Isayev.

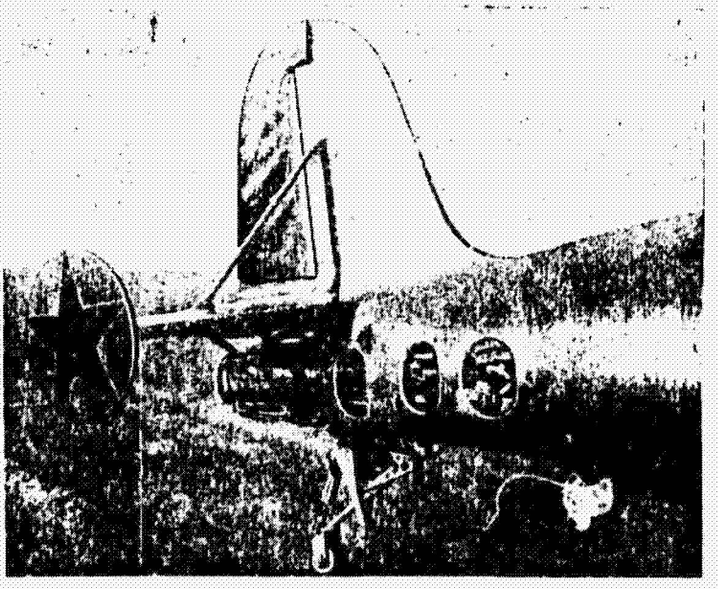
The data of the engine are: nominal thrust 1100 kg; pressure in chamber 19 atm; specific impulse 204 sec; fuel -- nitric acid and kerosene; ignition -- glow plug; weight 48 kg. /233

Due to the difficulty of adjustment of the fuel component feed system pump, A. I. Isayev, on the suggestion of V. F. Bolkhovitinov, developed an extractive feed system for the D-1-A-1100 engine in cooperation with M. V. Mel'nikov. The use of this feed system required a redesign of the aircraft.

The first flight of an interceptor with the D-1-A-1100 engine was held on 15 May 1942, by test pilot G. Ya. Bakhchivandzhi.



The D-1-A-1100 Liquid-Fueled Rocket Engine



Installation of the D-1-A-1100 Engine in an Aircraft

After 1943, the D-1-A-1100 engine was modernized by A. M. Isayev. This version of the engine retained the basic dimensions of the chamber and nozzle of the D-1-A-1100 engine, in which the nozzle had spiral fins with constant spacing, the fins being

perpendicular to the axis of the nozzle, so that at the exit plane they approach the wall at an angle of 30°. The new nozzle had sextuple fins of variable spacing and variable slant. This allowed a decrease in wall thickness with a simultaneous increase in rigidity of the structure. /234

Aleksey Mikhaylovich Isayev

Like the D-1-A-1100, the nozzle was cooled with kerosene, the cylindrical portion of the chamber with the oxidizer, passing through a multiple spiral channel system. The head, as before, was spherical in shape; the spiral sprayers were located in a circle. at the center of the head was the starting unit, the sprayers of which were equipped with ball valves to prevent leakage and further combustion of the components when the engine was shut down. The engine operated in three modes: starting mode, then, depending on the position of the control lever, developing a thrust of 400 or 1100 kg.

State stand testing of the engine was conducted in October of 1944, after which it was installed on an aircraft, which performed the planned program of flight testing successfully with the LRE in operation.

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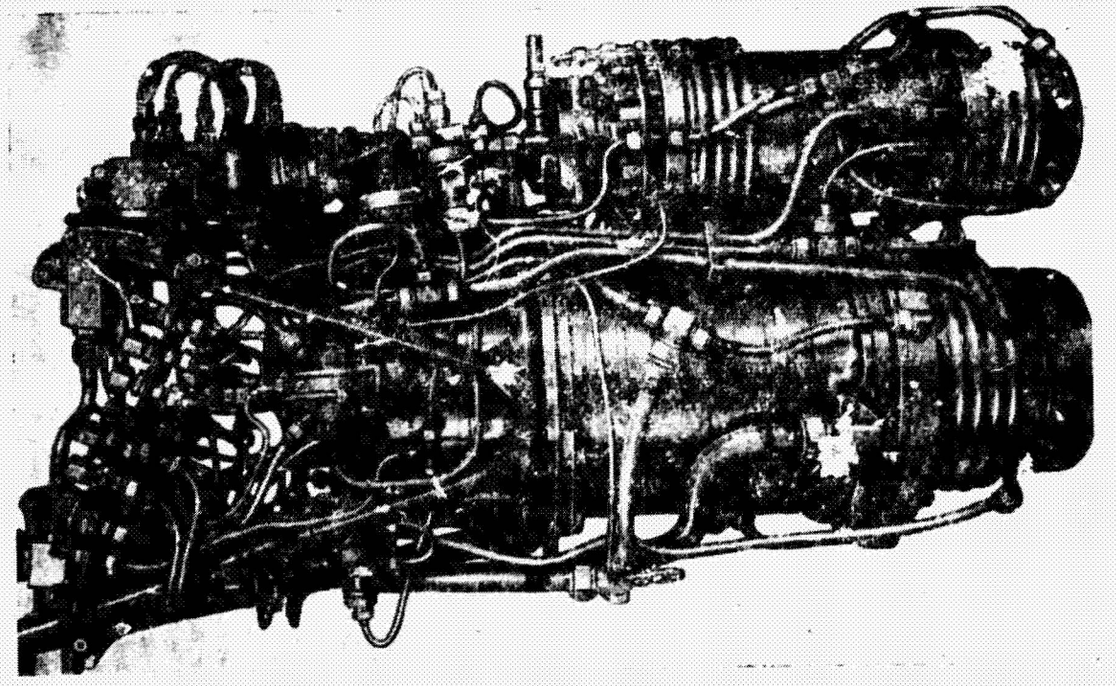

Exterior View of the RD-2M-3 Two-Chamber Engine

Aleksey Mikhaylovich Isayev (1908-1971), was born 24 October 1908 in Peterburg. After graduating from the Moscow Mining Institute in 1932, he first worked in construction, then in planning organizations, and beginning in 1934 at enterprises of the aviation industry. Together with V. F. Bolkhovitinov and A. Ya. Bereznyak, A. M. Isayev participated in the creation of the first Soviet aircraft with LRE, in which test pilot G. Ya. Bakhchivandzhi flew on 15 May 1942.

In 1944, he headed one of the design organizations involved in rocket engine building and was among the creators of many engines for rockets and spacecraft. Engines developed under the /236
leadership of Aleksey Mikhaylovich were carried on the Vostok-Vaskhod and Soyuz manned spacecraft and on automatic interplanetary stations.

A. M. Isayev was a member of the CPSU, a Hero of Socialist Labor, a Lenin and State Prize Laureate, a Doctor of Technical Sciences. A. M. Isayev was awarded four Orders of Lenin, the Order of the October Revolution and many medals of the USSR.

The team of L. S. Dushkin, of which we spoke earlier, developed aircraft LRE with turbine pump units, designed as main engines for the aircraft and eliminating the need to use a propeller motor installation. This family of engines included the RD-2M, RD-2M-3, RD-2M-3V, RD-KS-1 and others.

The RD-2M engine burned nitric acid and kerosene, its gas generator operated on hydrogen peroxide. Its maximum thrust was 1400 kg, minimum thrust 350 kg; the duration of continuous operation was 40-60 sec. After 40-45 operational cycles, the combustion chamber was replaced with a new one. The operating life of the turbine pump unit (with two-stage turbine) and the vapor-gas generator was 1.5 hr. The combustion chamber carried single-component spiral-type sprayers; ignition was by an electric spark plug.

The RD-2M-3 engine was developed in 1944. In contrast to the RD-2M, it had an additional combustion chamber, developing a maximum thrust of 300 kg and a minimum thrust of 100 kg.

The next engine, the RD-2M-3V, with a thrust of 2000 kg, was designed for an experimental aircraft; its development was begun in 1944. In 1947-1948, the engine underwent further testing. As in earlier models, the fuel was supplied by a turbine-pump unit; the unit had three centrifugal pumps: for nitric acid, kerosene and 80% hydrogen peroxide. A solid catalyst was used to break down the hydrogen peroxide.

The RDKS-1 regulated engine, designed for multiple starts, utilized liquid oxygen and ethyl alcohol. The thrust of the engine in the maximum mode was 1500 kg, in the minimum mode --

300 kg; the specific impulse at the nominal mode was 205-210 sec. The cooling was combined -- external flow cooling in combination with internal film cooling. The component for creation of the film entered the cylindrical portion of the chamber and the expanding portion of the nozzle. The sprayer head-prechamber /237
was made in the form of a cone expanding toward the chamber. The oxygen sprayers were jet type; the alcohol sprayers were centrifugal. The walls of the chamber and the nozzle were spirally ribbed. Fuel was supplied by a turbine-pump unit. The turbine gas was produced by decomposition of 80% hydrogen peroxide in a gas generator. Testing of the RDKS-1 was completed in 1947.

L. S. Dushkin began developing the RDD-203 rocket and its KRD-600 combined engine in 1939.

The KRD-600 had two stages of thrust -- 5000 and 1100 kg. During operation in the first stage -- with 5000 kg thrust -- the fuel used was powder, which filled the combustion chamber; the pressure in the chamber was 220 atm; the operating time of the engine was 0.5-0.6 sec, depending on the initial temperature of the charge.

Operation in the second stage -- with 1100 kg thrust -- utilized liquid fuel -- nitric acid and kerosene; the feed system was extractive, using a powder-type pressure accumulator; the pressure in the combustion chamber was 42 atm; specific impulse 220 sec; operating time 9 sec.

The combustion chamber was made of steel and was not cooled, the nozzle was made of copper, cooled by a copper heat-accumulating insert. The sprayers were centrifugal (spiral type) with a plug which burned out as the engine operated in the first stage.

Test firing of the rocket was conducted in 1939-1940, initially from a nonmoving support, then from a mechanized 10-charge launcher.

The basic data on the RDD-203 are: diameter 200 mm; length 3000 mm; launch weight 220 kg; payload 50 kg; design range 23 km.

In addition to these engines, L. S. Dushkin directed the development of LRE designed for various purposes.

Beginning in 1954, the Design Bureau headed by S. A. Kosberg worked on LRE for aircraft using one-component fuel, then after 1956 -- two-component fuel. This office soon developed a number of medium-thrust LRE designs which were widely used in rocket and space technology.

Tsiolkovskiy pushed back the boundaries of human knowledge and his ideas on rocket flight in space have only today begun to be realized in their full grandiosity.
S. P. Korolev

Conclusions

After the victorious conclusion of the Great Patriotic War, /238
we could only expect to achieve success in the study of space by means of the use of powerful LRE with high characteristics, including reliability. Development of theoretical problems of rocket dynamics, the creation of rocket designs with high payload efficiency and the study of systems for stabilization and control of the flight of these rockets were also required, as well as the development of the ground equipment for spaceports.

The forces of all workers in the area of space technology were devoted to the solution of this group of problems in our country.

As a result, the Soviet Union continued along the path to space and opened the space era on 4 October 1957 with the launch of the world's first artificial Earth satellite.

Since 1949, high altitude rockets had been launched systematically in the USSR. One of the first rockets -- the V-2-A -- was a geophysical rocket, designed to study the upper layers of the atmosphere, photograph the spectrum of the sun, perform medical and biological investigations, etc.

The V-5-V rockets were designed for astrophysical, geophysical, medical-biological, ionospheric and other studies. On these rockets, experiments were continued with animals, including their return to Earth.

The engines of the V-2-A and V-5-V rockets, designed by the GDL special design bureau, were single-chamber engines, burning liquid oxygen and alcohol fuel. The fuel was carried in load-bearing tanks (the walls of the tank formed the skin of the rocket) by a turbine pump unit driven by the products of decomposition of hydrogen peroxide. Operation of the V-2-A and V-5-V and similar models allowed the designers to go on to the creation of /240
morepowerful, improved models, making basic changes in the design of the engines.

On 12 April 1961, the world's first manned space flight occurred. A multistage rocket designed by Academician S. P.

Korolev carried the Vostok spacecraft and pilot-cosmonaut Yuriy Alekseyevich Gagarin into orbit.

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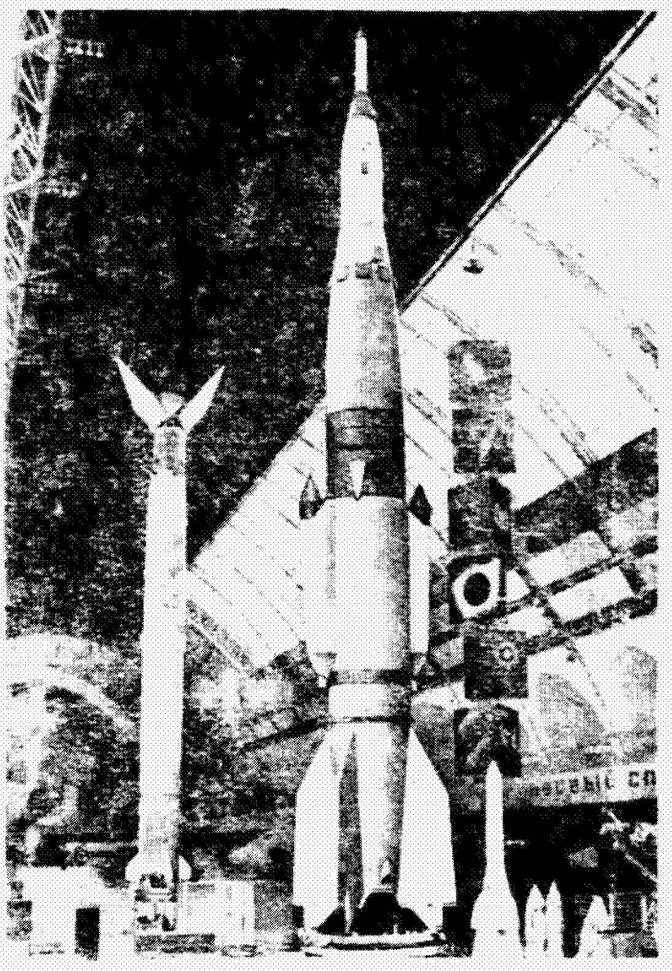


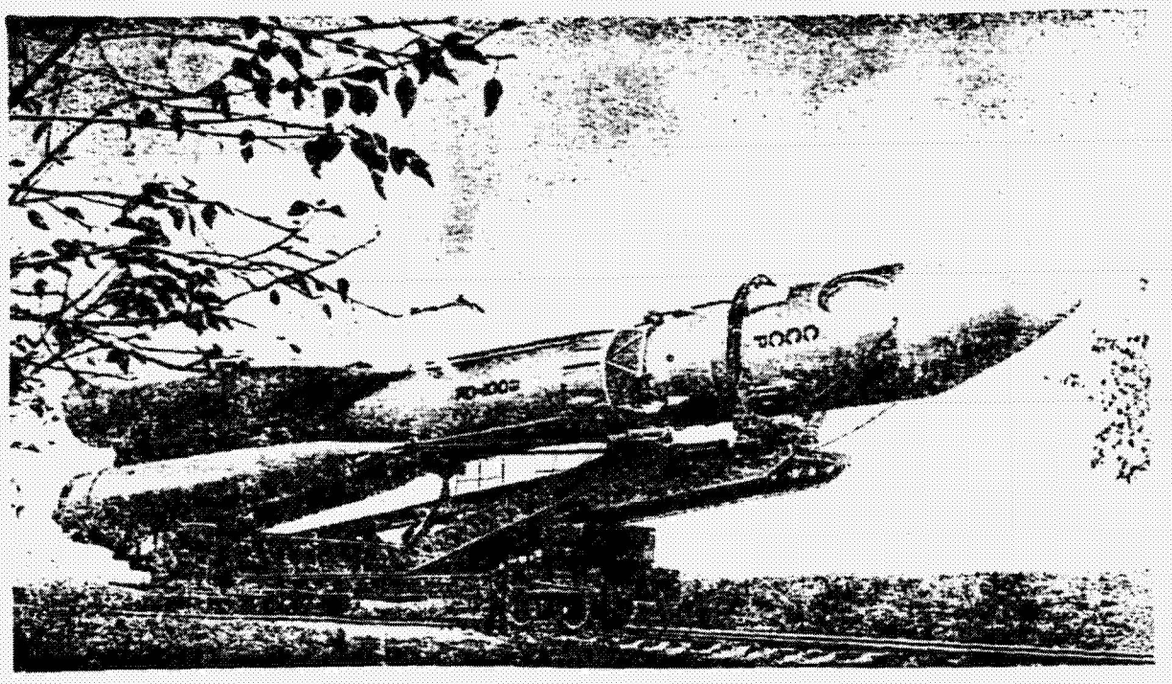
The V-5-V and V-2-A Geophysical Rockets

The three-stage Vostok booster rocket consists of four side units (first stage) located around the central unit (second stage). Above the central unit is the third stage of the rocket. Each of the first stage units carried a type RD-107 four-chamber LRE, while the second stage carried a four-chamber type RD-108 engine. These engines, created by GDL-OKB, have been in use since 1957 and are still used.

Burning liquid oxygen and kerosene, the RD-107 engine develops a thrust of 102 t in a vacuum with a specific impulse of 314 sec, while the RD-108 develops 96 t with a specific impulse of 315 sec.

The main combustion chambers of each engine, like the guidance chambers, are supplied by a common turbine pump unit; the RD-107 includes two, the RD-108 -- four guidance chambers.

/241



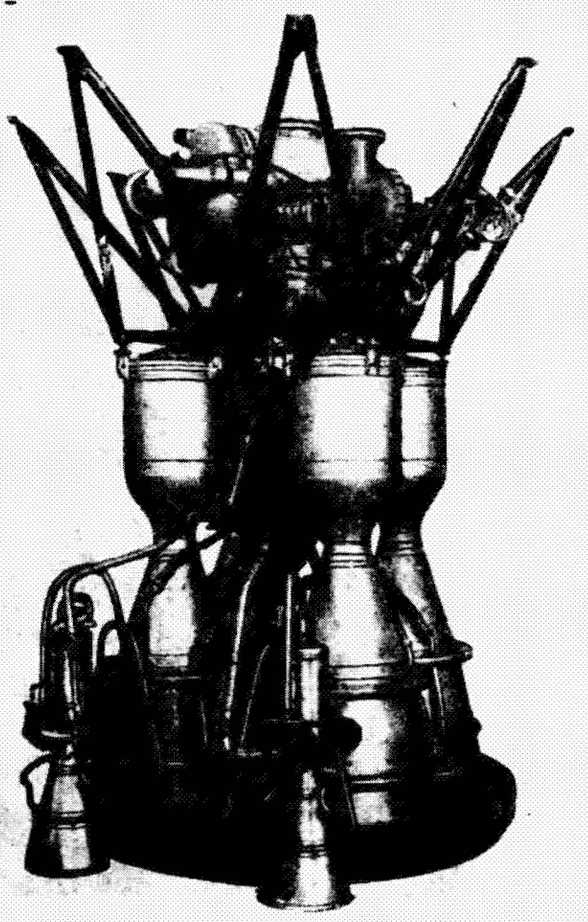
Overall View of the Vostok Rocket

The use of several chambers in a single engine allows the length of the engine and the weight of the rocket to be reduced. Furthermore, it is easier to achieve a stable combustion process in a chamber of smaller volume.

The turbine pump unit (TPU) consists of a gas turbine, two centrifugal pumps supplying the main fuel components, and two supplementary pumps, driven through an rpm multiplier and designed to feed liquid nitrogen and hydrogen peroxide to the TPU. The liquid nitrogen, used to blow out the tanks, is evaporated in a tubular heat exchanger located in the body of the turbine.

The combustion chamber of the RD-107 and RD-108 engines is a cylindrical soldered-welded structure with a flat sprayer head. The fire wall of the chamber is made of heat-resistant bronze in those areas most heavily thermally loaded. The outside of the fire wall is finned. The tips of the fins are connected to the /244
outer supporting jacket by a high-temperature solder applied in a vacuum furnace. In less thermally loaded parts, the fire wall is attached to the jacket by the same solder by means of a corrugated insert. The outer, cold wall is a part of the load-bearing system of the structure, allowing strong, light combustion

chambers to be made. The head of the chamber carries two-component bronze sprayers, assuring good mixing of the components and, consequently, complete combustion. The combustion chamber has not only external flow cooling by the fuel, but also internal film cooling.



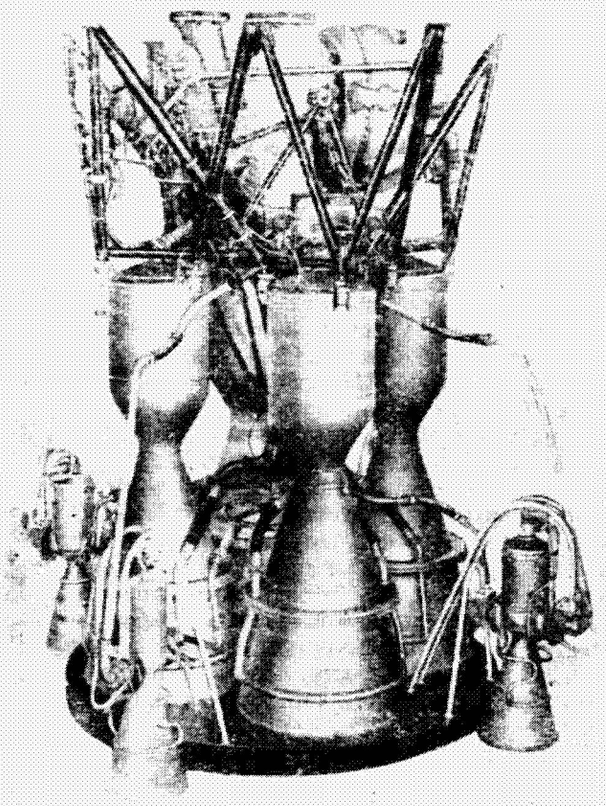
General View of RD-107 Engine

The third stage carries a single-chamber LRE with four guidance nozzles. /242

During the powered section of the flight, the engines of the central and side units at first operate simultaneously. After the fuel of the side units is exhausted, their engines are shut down and the side units are separated from the central unit, the rocket engine of which continues to operate at full thrust. After the fuel of the central unit is exhausted, the third stage engine starts up and the third stage is separated from the central unit. The third stage is shut down and the spacecraft separated from the booster by a control system when the design velocity, corresponding to injection of the spacecraft into the desired orbit, is reached.

Another Soviet booster rocket which has been widely and successfully used for many years for comprehensive study and the performance of practical tasks in near-Earth orbit is the Kosmos rocket. The two-stages of this rocket are located one above the other.

The first stage of the Kosmos rocket utilizes an RD-214 engine, which develops a thrust of 74 t in a vacuum with a specific impulse of 264 sec. /248



General View of the RD-108 Engine

The engine has the greatest thrust and specific impulse of all known engines of this type, burning nitric acid-hydrocarbon fuel. The engine is a four-chamber engine, with a common turbine pump unit. The combustion chamber had external flow cooling. Furthermore, the peripheral sprayers form a protective fuel layer along the walls. The starting fuel, hypergolic in combination with the basic oxidizer, is poured into the fuel line before the pump. The engine has thrust and fuel consumption regulators, allowing flexibility of its flight program. The RD-214 engine was designed betweer 1952 and 1957 and has been flying since 1957. It is one of the early developments of the GDL-OKB. /243

The second stage of the Kosmos rocket carries an RD-119 engine, developed by GDL-OKB between 1958 and 1962. The engine burns liquid oxygen and unbalanced dimethyl hydrazine, developing a thrust of 11 t in a vacuum. It has the highest specific impulse of all oxygen engines using non-volatile fuel. The specific impulse of the RD-119 engine in a vacuum is 352 sec, of the combustion chamber -- 358 sec.

Theengine has a high altitude nozzle profile. The gas for the TPU is produced in a single-component gas generator, utilizing the basic fuel. The design of the engine makes wide use of the latest structural materials, basically titanium. The steering system of the engine is designed for control and orientation of the second stage of the rocket in flight. Control is achieved by redistribution of the spent turbine gas among the guidance nozzles. Ignition is pyrotechnical. Preliminary spinning of the turbine pump unit is by a powder charge in the gas generator. /249

The Kosmos Booster Rocket

Since 1965, the Soviet Union has performed deep studies of high and super-high energy cosmic rays utilizing apparatus carried on the heavy proton space stations.

The engines of the proton booster rocket are made according to a new, highly perfected design. The power of the proton engine installation is three times that of the Vostok booster rocket. The high pressure in the combustion chamber, the high quality achieved in the processes of mixture formation and combustion and the care given to development of the processes of exhaust of the combustion products from the nozzle and design of the feed system have allowed these powerful engines to be made quite small with exceptionally high characteristics.

Low power rocket engines are used in manned spacecraft and unmanned spacecraft for various purposes. One such engine is the correction device designed by A. M. Isayev, used to correct the orbits of the Molniya-1 communications satellites and the flight trajectories of automatic interplanetary space probes such as the Zond spacecraft.

This engine operates on liquid fuel, developing a thrust of 200 kg in a vacuum for a period of 65 sec.

The achievements of Soviet rocket and space technology have been extensively exhibited in the "Space" Pavilion of the Academy of Sciences USSR at the Exhibition of Achievements of the National Economy in Moscow, in the State Museum of the History of Astronautics imeni K. E. Tsiolkovskiy in Kaluga, in the GDL Museum in Leningrad and a number of other museums and exhibitions.

Almost a half century ago, K. E. Tsiolkovsky wrote: "Man will not always remain on the Earth, but in his pursuit of light and space will first penetrate timidly beyond the limits of the atmosphere, then master all of solar space." /252

This prediction of the great genius is today being confirmed as a scientifically well-founded prediction.

The first steps on the path to space were made using a liquid-fueled rocket engine. The solution of many current problems requires improved LRE as well as engines of basically new design.

The use of fluorine fuel can increase the specific impulse of LRE to approximately 500 sec; the specific impulse of a nuclear rocket engine with a solid-phase reactor can reach 1000 sec, with a gas-phase reactor -- 2500 sec.

The use of thermonuclear energy can be expected to be still more effective.

The electric rocket engines now being designed will significantly expand our capabilities in the area of space technology.

It is possible that in time the achievements of science and technology will show us means and methods of penetrating outward into the universe so effective that progress in the area of astronautics will exceed our most optimistic dreams.

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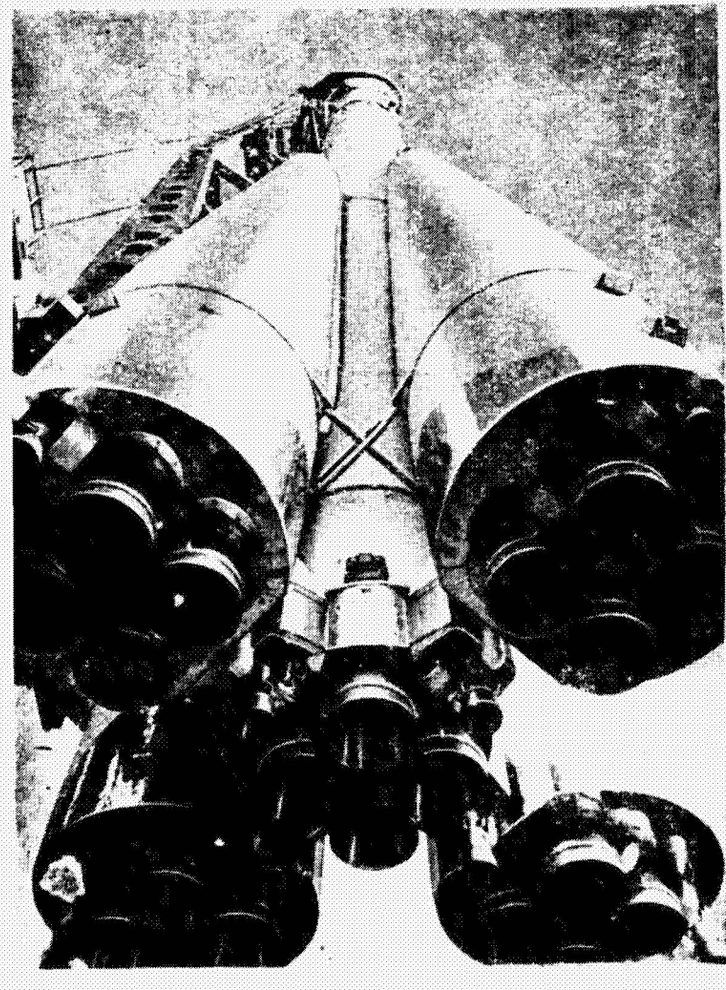

The Vostok Booster Rocket

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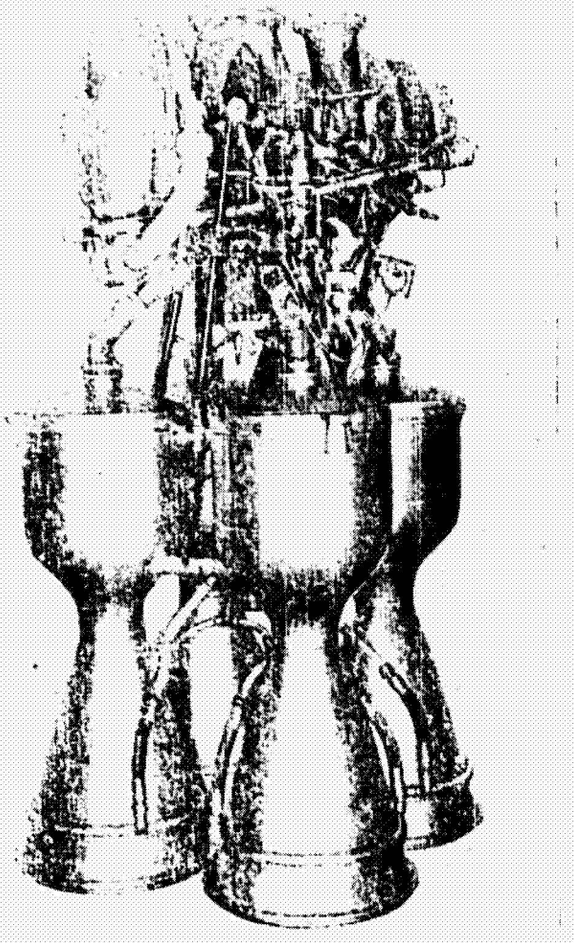

General View of the RD-214 Engine

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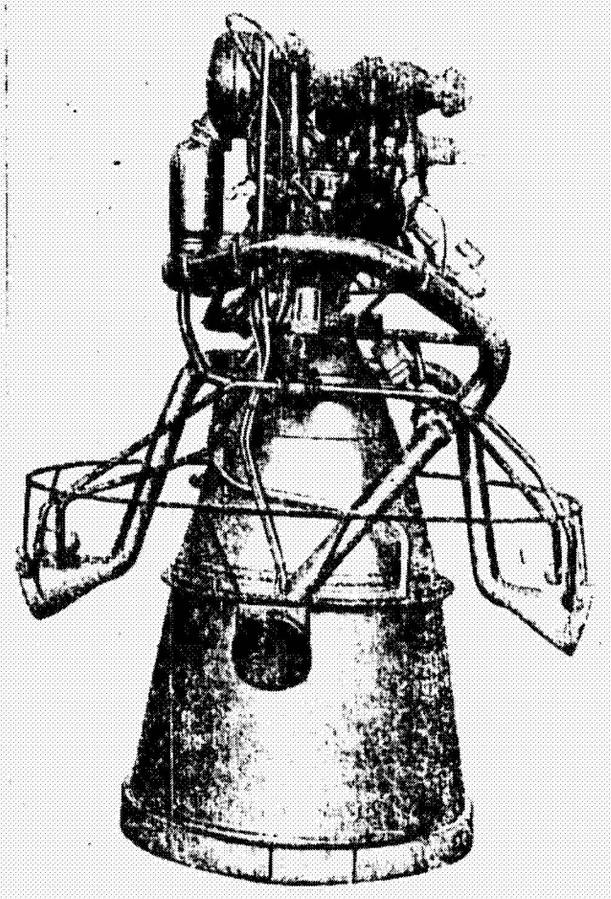
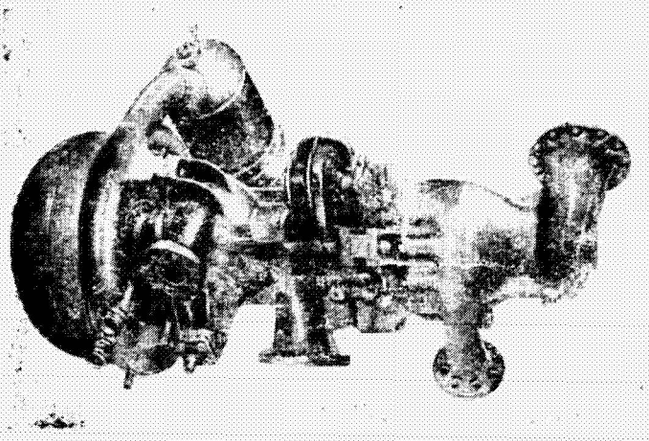


General View of the RD-119 Engine



General View of the RD-119 Engine Turbine Pump Unit

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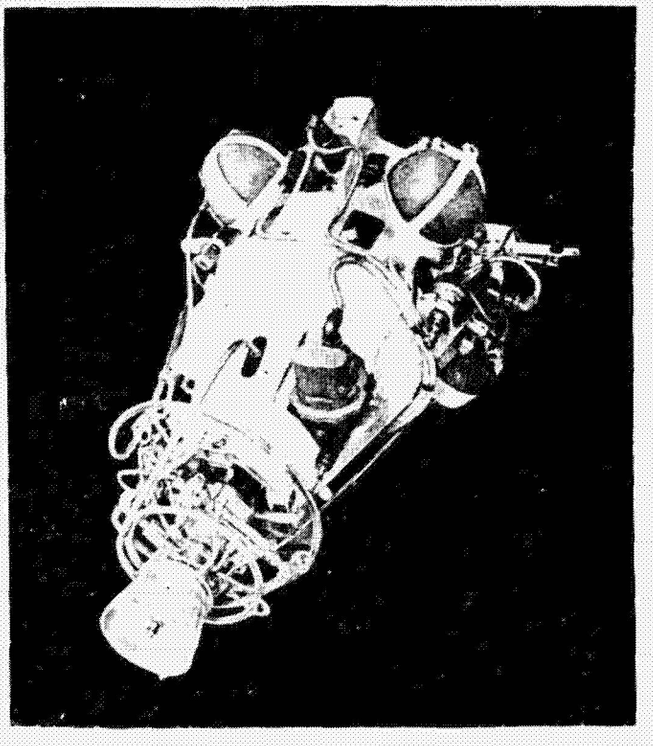

The Correction Engine Designed by A. M. Isayev

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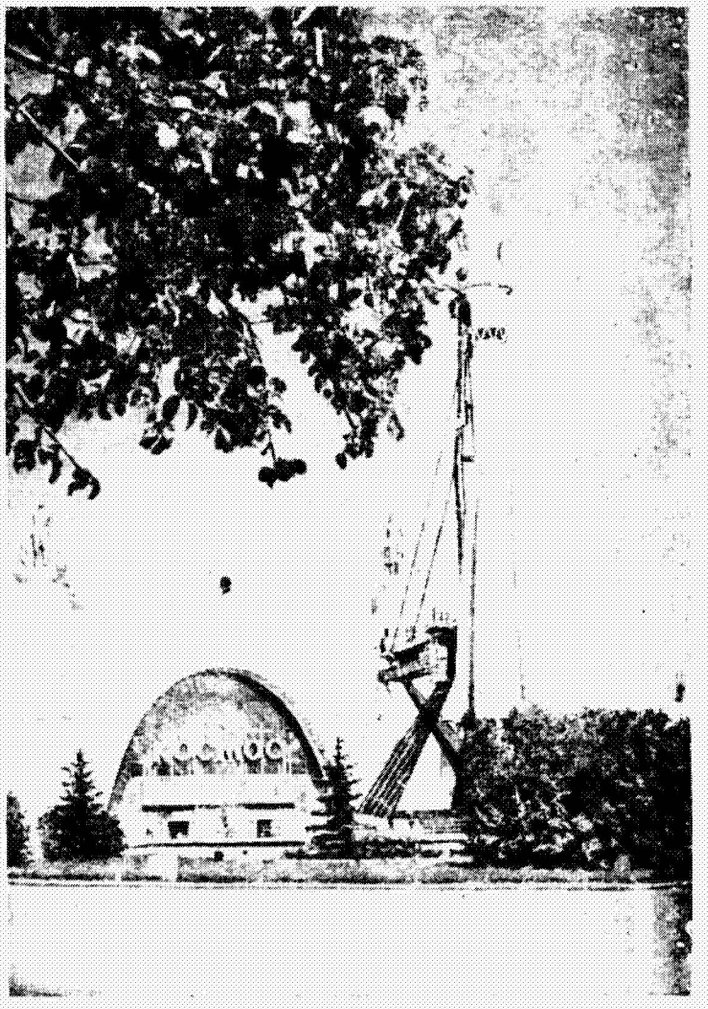

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16. Abstract This book covers the history of the creation of Soviet liquid-fueled rocket engines. The works of K. E. Tsiolkovskiy and Yu. V. Kondratyuk on the selection of engine and rocket designs, including multi-stage designs, are described. The properties of fuel components for liquid-fueled engines and the work of F. A. Tsander in the area of the creation of original plans for spacecraft and rocket engines are studied. The use of elements of the structure of the rockets as additional fuel is analyzed; the creative path of a number of leading Soviet scientists is traced. The activity of the first Soviet rocket organizations is discussed and the liquid-fueled rocket engines and aircraft rocket engines which they created are analyzed. Some modern, high-power liquid-fueled rocket engines are described.

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